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## Review of Quantum navigation

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# Review of Quantum navigation

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**Abstract.** With the continuous improvement of the demand for navigation and positioning services, the accuracy and security of traditional navigation systems have become the limits of future applications. The development of quantum technology has become the hope of a new generation of navigation systems. This paper summarizes and analyzes the research status of quantum active positioning system and passive positioning system and their core technologies, and compares their advantages and disadvantages, and the future development trend of the corresponding technology. Finally, based on the analysis of the problems of quantum navigation system, this paper proposes a solution that may be applied in the future, and puts forward the prospect of the development of quantum navigation system.

## 1.Introduction

The position of an object in space can be referred to as its spatial information. Since ancient times, people's daily life has always been closely related to time and space information. We have made great efforts to get our own accurate spatial information. According to statistics, more than 85% of our information is related to time and space. People's demand for positioning and navigation is increasing, and the dependence on location services is becoming stronger. The breadth and depth of application of positioning and navigation are also gradually expanding. In March 2017, the European Navigation Satellite System Authority (GSA) released the GNSS (Global Navigation Satellite System) Market Report, which is expected to cover the global GNSS industry in 2025, including eight application areas such like location services, roads, aviation, maritime, agriculture, where location service and road applications account for more than 90% of the market. It can be seen that people's increasingly strong dependence on positioning and navigation makes the breadth and depth of the application field of positioning and navigation gradually expand.

Although the application of GNSS represented by GPS has been widely used, its accuracy and security issues have begun to become prominent in current practical applications. In indoors, underground and cities, canyons and other scenes, GPS cannot provide continuous and accurate services due to occlusion of signals. In addition, radio signals can be eavesdropped or even rewritten, which also causes GPS security to be challenged. Therefore, the main challenge for next-generation navigation technology is high availability and high credibility. In this case, a quantum technology-based navigation system may be the solution. The Quantum Positioning System (QPS) was first proposed in 2001 by Dr. Giovannitti of the Massachusetts Institute of Technology (MIT) in the journal Nature. It is proved by calculation that the quantum entanglement and compression characteristics can further improve the positioning accuracy. By means of the preparation of quantum entangled state and its transmission technology, QPS no longer uses electromagnetic waves, which can not only break through the limits of traditional positioning accuracy, but also provide good protection in terms of confidentiality and anti-



interference ability. Its energy consumption is much smaller than that of traditional ones. The system may bring fundamental improvements to the miniaturization, continuous working hours and stealth performance of the device.

In addition to satellite-based quantum active navigation systems, quantum passive navigation systems based on inertial navigation will also be an important means of exploring future navigation. In modern applications, inertial passive navigation is often combined with satellite active navigation for better results. In addition, the process of passive navigation does not exchange information with the outside world, which makes the passive navigation system have high credibility and high availability, which makes it a very popular military application, such as nuclear submarines and other important moving targets that need to hide their position. This paper mainly introduces quantum navigation system from the aspects of quantum navigation classification, core technology and development trend. The second chapter introduces quantum active navigation system and its key technologies. The third chapter introduces quantum passive navigation system and its key technologies. The fourth chapter introduces the development prospects of quantum navigation.

## 2. Quantum active navigation system and key technologies

QPS can be divided into two categories: quantum active navigation system and quantum passive navigation system. The quantum active navigation system adopts the method of transmitting and receiving quantum signals. The positioning process usually uses satellite as the signal source. The quantum passive navigation uses quantum sensor device to locate, does not need external signals, and is usually positioned by detecting acceleration.

### 2.1 Quantum active navigation system

Active navigation systems typically use satellites as the source of ranging, and quantum active navigation is no exception (see Figure 1). In 2004, Dr. Bahder of the US Army Research Laboratory proposed an interferometric quantum positioning system [1].

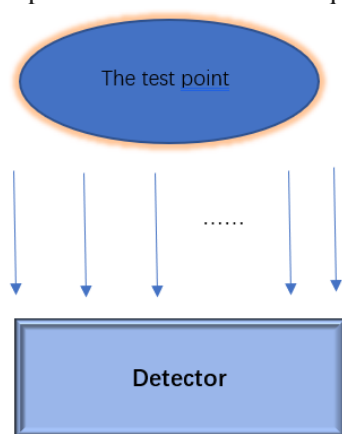


Figure 1 Quantum satellite navigation

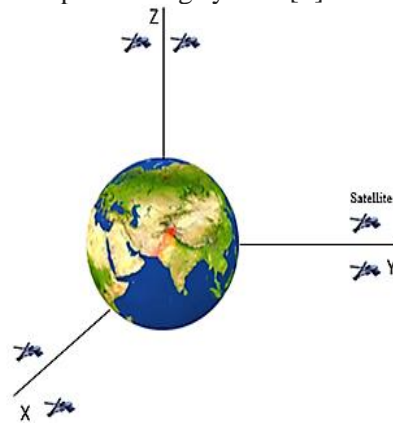


Figure 2 Quantum satellite navigation

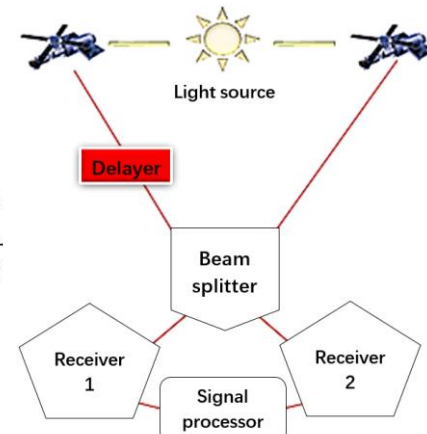


Figure 3 Structure of each baseline

The system uses a system structure similar to that of traditional satellite navigation. One of the schemes consists of three baselines, each of which contains two low-orbiting satellites with the Earth's center as the coordinate origin, and the three baselines form a coordinate system perpendicular to each other, as shown in Figure 2. In addition, each baseline includes a semiconductor light source, a delay filter, a beam splitter and two photon detectors. (see Figure 3) First, the light source respectively emits beams to the two satellites, and after reflection, reaches the beam splitter, and then the splitter respectively transmits the two photon detectors, and by adjusting the delay time, the counting rate of the observed entangled photons is minimized. At this point, it can be known that the two paths have the same propagation time. Finally, by calculating the distance between the satellites and the delay generated by the delay filter, the precise position of the target can be calculated by the mathematical platform.

## 2.2 Key technologies of quantum active navigation system

**2.2.1 Preparation of photon entangled states.** Quantum satellite navigation systems require many entangled photons during the ranging process. At present, there are various methods for preparing entangled states, such as parametric down-conversion effects of nonlinear crystals [2], ion traps [3], and atomic-optical cavities [4]. The entangled state is prepared by the Spontaneous Parametric Down-conversion (SPDC) method. Use laser pass the nonlinear crystal by the spontaneous parametric down-conversion process of laser-pumped nonlinear optical crystals, and the twin photon pairs produced have extremely high entanglement purity. The preparation process is controllable and has a certain strength. Using the second-order nonlinear effects in nonlinear optics, the pump photons have the probability of being split into a photon pair by scattering. The two photons in the photon pair can be arbitrarily called signal photons and idle photons (as shown in Figure 4). When the signal photon and the idle photon are in a state of polarization perpendicular to the pump photon, an I-type association is formed, and when the polarization state of the signal photon and the idle photon are perpendicular to each other, a type II association is formed (Fig. 5).

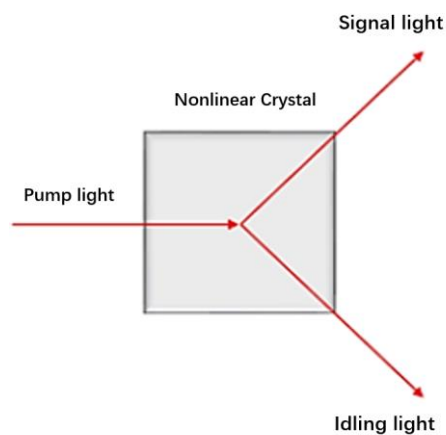


Figure 4. SPDC process

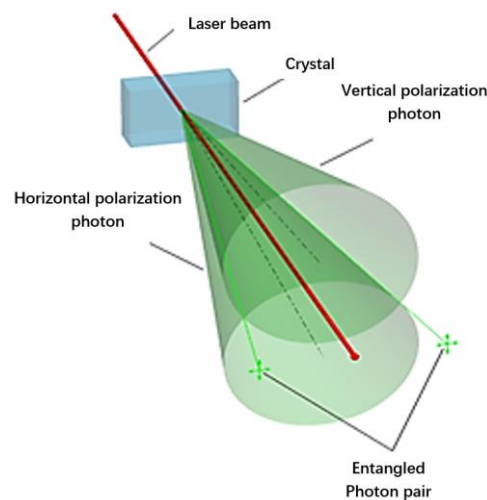


Figure 5. II SPDC process

An ion trap is a device that confines ions in a confined space by an electromagnetic field. The study of the preparation of entangled states by ion traps is mainly to realize the entangled state of two atoms or even multiple atoms in the trapped ion system. This method has two main advantages: First, the ions are trapped in a highly vacuum environment, almost isolated from the "interference" condition, so it has a relatively long decoherence time; the second is the preparation of the initial state and the measurement of quantum states has a very high fidelity phase efficiency, which is beneficial to quantum computing and quantum information processing. The study of the preparation of entangled states by cavity quantum electrodynamics (Cavity-QED) is gradually carried out with the development of cold atom technology and photoelectric testing technology. The electromagnetic field pattern trapped in the microcavity is enhanced or suppressed by the boundary constraints of the cavity, trapping the trapped atoms in a high-quality cavity, and storing the quantum information in the atomic energy state. Since the atoms in the cavity are coupled with the cavity mode field, the interaction between the atoms and the light field is caused. Therefore, the cavity system can be used to prepare the entangled state of the atom and the light field. The research status of different methods for preparing entangled states can be summarized. (as shown in Table 1).

Table 1. Research status of the three main methods for preparing entangled states

Method	Scholar	Research results	Disadvantage
SPDC	Franson	Realizing energy-time non-local interference of two particles	The time at which two photons are simultaneously generated is unknown.

Ion trap	Kwiat's group	Achieve high correlation of two photon momentum, position, polarization, direction and other degrees of freedom [5].	The conversion efficiency is extremely low, and only 4 pairs of entangled photons can be generated per 106 incident photons.
	Kurtsiefer's group	Optimized the method of entangled photon pair [6]	Can only be used in specific infrared areas.
	Pan Jianwei'S Group	In 2014, a five-photon entangled state was prepared, and the terminal-state quantum state stealth transmission was realized.	The universal application of quantum navigation has not yet been realized.
	Guo Guangcan's team	The eight-photon entangled state was prepared, which set a new world record for the number of multiphoton entanglement preparations and operations.	The universal application of quantum navigation has not yet been realized
	US NIST Ion Trap Group	A non-maximally entangled state is prepared [7].	Less entangled state
	Steinbach	A scheme for preparing the maximum entangled state of N ions is proposed [8].	Not yet implemented
Cavity quantum electrodynamics (C-QED)	Solano	A scheme for preparing any of the four Bell states is proposed [9].	Not yet implemented
	Zheng Shibiao and Guo Guangcan	A light field entangled state is prepared, kind a continuous variable entangled state.	Not yet implemented
	Guo Guangcan	A three-light field W state, a discrete variable entangled state [14] was prepared.	Not yet implemented

**2.2.2 Capture, Tracking and Aiming Systems and Techniques.** Quantum satellite navigation systems also require spatial optical communication and ATP technique (acquisition, tracking and aiming). The basis of ATP technology comes from the techniques of optical positioning, detection and tracking commonly used in satellite laser communication. The tasks of system include the acquisition and high-precision tracking of beacon light transmitted by satellite communication terminals, and the high efficiency and high polarization-preserving reception of on-board quantum signal light. The difficulty of spatial ATP technology lies in two aspects. One is the requirement of high precision. Considering the influence of spatial loss on the bit error rate, the quantum light divergence angle in spatial scale quantum communication is usually close to the optical diffraction limit, so the beam must aligned in micro radians level( $\mu\text{rad}$ ); the second is the requirement of high stability, The system is affected by factors such as atmospheric channel loss, satellite platform interference, and space thermal environment. A good ATP system work well in those situations. The design of the ATP system binds the mechanical rotating platform to the optical antenna and automatically adjusts the received optical signal to ensure the quality of the reception. Usually, the system operation process consists of coarse tracking and fine tracking. The coarse tracking part captures the target in a large range ( $\pm 1^\circ \sim \pm 20^\circ$ ). After the capture, the aiming and real-time tracking accuracy of the target can be achieved through the fine tracking system. Up to ( $1\text{-}10 \mu\text{rad}$ ). The overall framework of the system is shown in (Figure 6).

Table 2. Progress in research on ATP technology in various countries

Method	Scholar	Research results	Disadvantage
SPDC	Franson	Realizing energy-time non-local interference of two particles	The time at which two photons are simultaneously

<b>Ion trap</b>	Kwiat's group	Achieve high correlation of two photon momentum, position, polarization, direction and other degrees of freedom [5].	generated is unknown. The conversion efficiency is extremely low, and only 4 pairs of entangled photons can be generated per 106 incident photons.
	Kurtsiefer's group	Optimized the method of entangled photon pair [6]	Can only be used in specific infrared areas.
	Pan Jianwei'S Group	In 2014, a five-photon entangled state was prepared, and the terminal-state quantum state stealth transmission was realized.	The universal application of quantum navigation has not yet been realized.
	Guo Guangcan's team	The eight-photon entangled state was prepared, which set a new world record for the number of multiphoton entanglement preparations and operations.	The universal application of quantum navigation has not yet been realized
	US NIST Ion Trap Group	A non-maximally entangled state is prepared [7]. A scheme for preparing the maximum entangled state of N ions is proposed [8].	Less entangled state Not yet implemented
	Solano	A scheme for preparing any of the four Bell states is proposed [9].	Not yet implemented
<b>Cavity quantum electrodynamics (C-QED)</b>	Zheng Shibiao and Guo Guangcan	A light field entangled state is prepared, kind a continuous variable entangled state.	Not yet implemented
	Guo Guangcan	A three-light field W state, a discrete variable entangled state [10] was prepared.	Not yet implemented

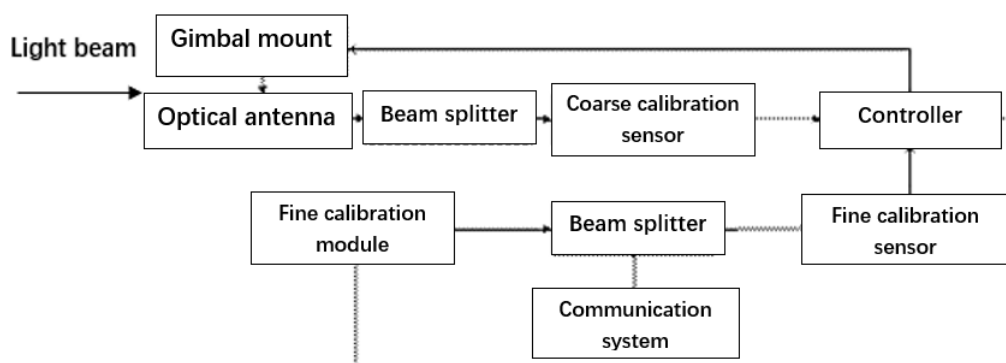


Figure 6. ATP system frame

### 2.2.3 Quantum clock synchronization technology.

The quantum clock synchronization is derived from the quantum entanglement of pairs of quantum (photons or atoms). In quantum active navigation systems, positioning and clock synchronization are two relatively independent processes. Through the second-order quantum coherence, the clock difference between the user clock and the system clock located near the origin of the coordinate system is accurately measured, and the user clock is synchronized to the system clock. The synchronization process of the satellite-based QPS does not require the distance between the user clock and the system clock. In addition, since the two-photon coincidence count measurement of the HOM interferometer

only requires the clock to remain stable for a short measurement period, clock synchronization has only short-term stability requirements for the user clock and the on-board clock, and there is no long-term stability requirement. However, the system clock located near the origin of the coordinate system should have good long-term stability to maintain accurate system time for a long time. The research results of quantum clock synchronization technology are shown in Table 3.

Table 3. Research results of quantum clock synchronization

Researcher	Result	limitation
Bahder	The time at which the entangled photon pair is received is measured by adjusting the optical path with the HOM interferometer to achieve synchronization [1].	The time delay crystal thickness needs to be adjusted and measured.
Valencia's Group	An experimental method is proposed that does not use a HOM interferometer, and the resolution can reach picoseconds in the three-kilometer range [11].	Unable to resist the effects of dispersion effects.
Exman's Group	A multi-QCS scheme based on N-particle W-state optimization is proposed [12].	The preparation of the N-particle W state is difficult so it is difficult to achieve.
Xie Duan	A quantum clock synchronization theory scheme using the structure of MZ interferometer is proposed to achieve higher accuracy requirements.	It takes two identical light paths thus difficult to achieve.
Yang Chunyan and Yuan Borui	A synchronous measurement method for satellite-based clock based on quantum second-order correlation function is proposed. In theoretical, time synchronization accuracy can reach 140fs.	It in the theoretical research stage, the feasibility of the complex application environment remains as problem.

### 3. Quantum passive navigation system and its key technologies

#### 3.1 quantum passive navigation system

The quantum passive navigation system is an inertial navigation system. Like the traditional inertial navigation system, its ranging and timing implementation does not depend on the real-time reception of spatial satellite signals. The state adjustment and positioning are performed by inertial devices. Therefore, the principle of the quantum inertial navigation system is to accurately locate the atomic inertia parameters after the atoms are disturbed. The quantum inertial navigation system has the same structure as the conventional inertial navigation. It composed of four parts: three-dimensional atomic gyro, accelerometer, atomic clock and signal processing module. Some structures also include spatio-temporal information transceiver module and attitude control module (Figure 7). Among them, atomic gyro, accelerometer and atomic clock are the core modules in quantum passive navigation system, and their performance directly affects the system positioning performance. The construction and experiment of quantum passive navigation systems are continuously researching. Representative quantum passive navigation systems are shown in Table 4.

Table 4. Research results of quantum inertial navigation

Year	organization	Result	Performance	Influence
2003	DARPA	High-precision inertial navigation system is realized by the principle of ultra-cold atomic interference [13].	The total position drift is $\leq 5\text{m/h}$ , the overall size is about $2\text{ft}^3$ , and the power consumption is $<100\text{W}$ .	It can compensate the position error caused by gravity change and realize full tensor gravity gradient measurement.

<b>2010</b>	DARPA	Launched the Micro-PNT project	The timing and inertial navigation unit is only 8mm <sup>3</sup> in size and consumes only 1w.	The navigation chip unit transitions from an ultra-low drift sensor to a self-calibrating sensor.
<b>2016</b>	DSTL	A QPS submarine navigation system with ultra-cold atoms was studied.	The accuracy is 1000 times higher than before, and the system is small.	Provide a backup navigation tool for urban traffic and self-driving vehicles.

### 3.2 Key technologies of quantum passive navigation system

**3.2.1 Atomic Gyroscope.** According to different working principles, atomic gyros can be divided into atomic interference gyro and atomic spin gyro. The atomic interference gyroscope is based on the atomic Sagnac effect (Figure 8). The cold atomic mass forms a cold atomic beam along the same parabolic trajectory in the opposite direction. Under Raman laser stimulation, an interference loop is formed due to the double loop atomic interference. The half of the phase shift difference is the phase shift caused by the rotation rate, so we can get the rotation rate. The theoretical value of the zero-bias drift of the atomic interference gyroscope is much lower than that of the traditional gyroscope. The theoretical precision can be the 1010 times of optical gyroscope. The atomic spin gyro is using the spin of an alkali metal atom's Larmor precession to achieve angular velocity sensing. There are currently two mainstream schemes for atomic spin gyros: one is the nuclear magnetic resonance atomic spin gyro (NMRG) using the dual-nuclear method, and the other is the atomic spin gyro operating in the spin-exchangeless relaxation state (SERFG). In the 1960s, the United States began research on NMRG. Since then, the research results of atomic gyros in the world have sprung up, as shown in Table 5.

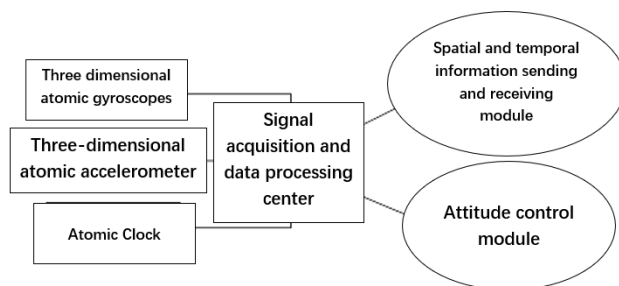


Figure 7. The diagram of quantum passive navigation system

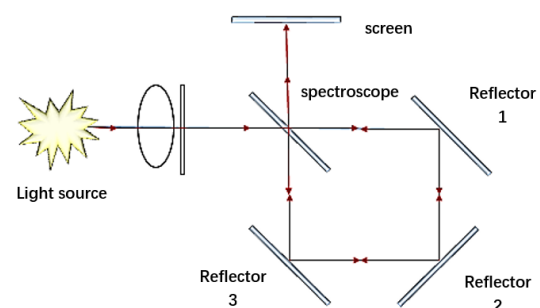


Figure 8. The diagram of Signac effect

Table 5. Research results of Atomic Gyroscope

Category	Organization	Result	Performance
Atomic spin gyroscope	Litton and Singer-Kearfott, USA	Litton's single-axis optical pump NMRG prototype [14]	4cm in diameter, 8cm in height, drift drift is 0.05°/h
		Singer-Kearfott's single-axis optical pump NMRG prototype [15].	1°/h. The diameter is 10cm, the height is 12cm, and the drift is 0.1°/h.
	Northrop Grumman, USA	In 2005, the engineering development of miniaturized atomic spin gyros began.	Undisclosed
		In 2007, the first prototype of nuclear magnetic resonance gyro was developed.	Its performance, size and power consumption are comparable to navigation-grade fiber optic gyroscopes.
		In 2012, an atomic spin gyro prototype was prepared [16].	The size is only 10cm <sup>3</sup> , the zero-deviation drift is better than



Atomic interference gyroscope	Princeton University	In 2005, produce a SERF atomic spin gyro.	0.05°/h, and the angular random walk is better than 0.01°/√h.
	Beijing Aerospace University, Stanford University	In 2008, a new generation of SERF atomic spinning gyros was prepared [17]. Successfully observed the gyro effect.	The zero offset drift is 0.04°/h, and the angle randomly walks 0.002°/√h. The angular random walk reaches 7.2e-8°/h. The angular random walk is 4.2e-3(°)/√h, and the zero offset drift has not been very good. Undisclosed
	Stanford University and Yale University	For the first time, an inertial effect was observed in a pulsed atomic interferometer.	Undisclosed
	Stanford University and Yale University	The first atomic interference type gyro prototype was realized by the combination of thermal atoms [28]. It has the highest precision of the atomic interferometer currently reported.	Its short-term sensitivity is $6e^{-10}$ (rad/s) / Hz <sup>1/2</sup> .
	LNE-SYRTE Laboratory, Paris Observatory, France	In 2000, based on the Raman pulse sequence, a cold atomic gyro was realized by using a cold 133 Cs atom pair.	The sensitivity of the rotational speed is 2.5e-6 (rad/s) Hz <sup>1/2</sup> .
	University of Hanover, Germany Stanford University	In 2009, they introduced a four-pulse Raman beam to coherently operate the cooled helium atom to form a butterfly atomic motion trajectory [18]. Use the laser cooling a Rubidium atoms and constructed a diatomic interference gyroscope.[19] Using a four-pulse Raman beam to coherently operate the ultra-cold cesium atom, an integrated miniaturized gyroscope is realized, which can measure the full inertia parameter.	The sensitivity of the rotational speed is close to 2.4e-7 (rad/s) / Hz <sup>1/2</sup> . The sensitivity of the rotational speed is close to 6.1e-7 (rad/s) / Hz <sup>1/2</sup> .

**3.2.2 Atomic accelerometer.** The discovery of the cold atom interference effect has led to the birth of atomic accelerometers, so its development is usually accompanied by the development of cold atom interference gyroscopes. Quantum accelerometers are several orders of magnitude better than traditional inertial devices. For example, if the position measurement error is less than 1 km after 100 days of sailing on a submarine, the submarine can perform long-term latency without satellite navigation. The research results of atomic accelerometers in recent years are shown in Table 6.

Table 6. Research results of atomic accelerometer

Year	Organization	Result	Performance
2006	NASA Jet Propulsion Laboratory	Completed the second-generation laboratory prototype of the atomic interferometer [20].	The acceleration sensitivity at the measurement period T = 100 ms is 3e-9 g/Hz <sup>1/2</sup> .
2008	H.Muller et al., Stanford University, USA	The use cesium atom to achieve accurate measurement of gravity.	Sensitivity reached 8e-9g/Hz <sup>1/2</sup> .
2008	LNE-SYRTE, France	The world leader of this field Accurate gravity measurement is achieved using ultra-cold cesium atomic interference [21].	Sensitivity reached 1.4e-8g/Hz <sup>1/2</sup> .
2003-2020	European Space Agency	The HYPER research program [22] was developed: measure the acceleration and rotation of two orthogonal directions using two atomic interferometers and two two-	The sensitivity of the gyroscope and the accelerometer in the two modes is 1e-9(rad/s)/Hz <sup>1/2</sup> , 2e12(rad/s)/Hz <sup>1/2</sup> and

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loop atomic gyros. The two atomic gyros can work in different modes.	$1\text{e-}10\text{g/Hz}^{1/2}$ , $4\text{e-}12\text{g/Hz}^{1/2}$ .
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#### 4. The development of quantum navigation technology

The quantum navigation utilizes the microscopic quantum characteristics of photons and can even surpass the limit of classical measurement to achieve higher precision. It is an emerging technology with great potential. The rapid development of quantum information technology has promoted the development of quantum device and quantum signal preparation, manipulation and storage related technologies. The solution of these technologies will provide strong technical support for the development of quantum navigation and positioning systems. In view of the factors that currently restrict the development of this field, we not only need in-depth study of key technologies more, but also needs to solve the following problem:

1. How to build a complete system framework. The entangled state preparation scheme and how the star baseline is proposed for the erection scheme. How to choose the corner reflector, HOM interferometer, and counter-matching devices. How to solve the problem of anti-noise measures (loss of photons) and protocols used for multiple users. The construction and testing of the quantum active navigation system are still in the theoretical stage, and the complete system framework has not been formed.

2. How to maintain the entangled state of spatial quantum signals. We need transmission of quantum signals in complex Long-distance space environments, thus the coherence of entangled photons and the stability of quantum navigation systems are difficult to maintain. Space optical communication has higher precision and confidentiality than electromagnetic wave communication, but it has become more sophisticated and fragile. Therefore, the perfect spatial optical communication system has higher technical requirements to ensure the stability of the system to ensure its superior performance.

3. How to combine quantum navigation with traditional navigation technology. At present, the development of traditional navigation technology has become more mature, but quantum navigation and positioning technology is only in beginning state. Therefore, the situation where quantum navigation technology and traditional navigation technology coexist will become the normal state for a long period of time in the future. Although quantum navigation positioning has higher performance, its implementation cost and technical complexity are much higher than traditional navigation. Therefore, traditional navigation can be fully applied to some areas where accuracy and safety are low, and its advantages are exerted.

#### 5. Conclusion

The quantum navigation positioning system is superior to the traditional classical measurement method and can achieve higher precision. It is an emerging technology with great potential. This paper reviews quantum navigation systems from the aspects of quantum navigation classification, key technologies and development trends of active and passive quantum navigation. From the research status of key technologies of quantum navigation systems, it takes a long time to realize the large-scale application of quantum navigation systems.

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