Research of An Improved Satellite-based Quantum Positioning System

Wei Fan[1, a]
[1]Universty of Rochester, Rochester, U.S

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Abstract: The accuracy of traditional GPS system is limited, and it is liable to be deceived and jammed. The problem of its application has become increasingly prominent. Based on quantum physics, quantum navigation technology has the potential to achieve high-precision navigation and positioning services. At present, the implementation scheme of baseline interferometric satellite-based quantum positioning system proposed by the United States requires six satellites to achieve positioning, and the cost of the system is high. This paper presents an improved satellite-based QPS system and describes it systematically. The whole QPS system includes the establishment of satellite-ground optical link, the acquisition of TDOA by entangled light, the process of ranging and positioning. Compared with the traditional baseline interferometric satellite-based QPS system, the number of satellites needed is reduced effectively.

1 INTRODUCTION

Global Navigation Satellite System (GNSS), represented by GPS, has been widely used, but its accuracy and security problems are becoming prominent in current applications. The accuracy of GPS can only reach meter level, and the GPS signal is easy to be rewritten and deceived. With the increasing demand for navigation and positioning services, the accuracy and security of traditional navigation systems such as GPS have become one of the bottleneck of future applications. With the development of quantum technology, the navigation system based on quantum technology may become an important solution. Quantum Positioning System (QPS) was first proposed by Dr. Giovannetti of Massachusetts Institute of Technology (MIT) in 2001 in Nature. It is proved that the quantum entanglement and compression properties can further improve the positioning accuracy. QPS can not only break through the limit of traditional positioning accuracy, but also provide good security in confidentiality and anti-jamming ability. It may fundamentally solve the security problem of transmission and it also breaks the stereotype of people's thinking in information transmission and coding. (Giovannetti, V, et.al, 2001; Marks, & Paul, 2014)

QPS can be divided into two categories: passive quantum positioning system and active quantum positioning system. Active QPS locates by sending and receiving quantum signals, and passive QPS locates by quantum sensor devices. Passive QPS based on inertial navigation obtains high-precision magnetic field and gravity field data through cold atom interference technology. Combining with traditional geomagnetic navigation and gravity navigation technology, it achieves high-precision navigation. The research group of Stanford University demonstrated the working principle of atomic interferometric gyroscope based on Sagnac effect. The British Defense Science and Technology Laboratory (DSTL), the Landragin Group of the French Observatory and the Rasel Group of Germany also carried out relevant research. China University of Science and Technology, Wuhan Institute of Physics and Mathematics of Chinese Academy of Sciences, Tsinghua University and China Academy of Aerospace Sciences and Technology, have studied quantum interference gyroscope, atomic spin gyroscope and nuclear magnetic resonance gyroscope based on quantum technology.

In addition to the passive QPS based on inertial navigation, the active QPS is also an important development direction. Active QPS uses entangled light with quantum entanglement to replace

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electromagnetic wave on the basis of GPS. By measuring the time difference of arrival (TDOA) of two interrelated entangled light beams, the distance between satellite and user and the spatial coordinates of user are calculated according to the acquired TDOA. The satellite-based interferometric QPS proposed by the US Army Research Laboratory, combined with the traditional satellite positioning idea and the optical quantum entanglement pulse interferometric ranging technology, is the first to put forward the design scheme of the satellite-based QPS to achieve positioning. It uses satellite to broadcast quantum signals. The basic structure of QPS is composed of three baselines which are composed of two groups of satellites with six known positions. The satellites are located in two focal points of a hyperboloid, and the user is at the intersection point of a hyperboloid consisting of a hyperboloid. But the disadvantage is that six satellites with three baselines are needed to participate in positioning, which is costly. (Giovannetti, & V, 2004)

Based on the existing active QPS, this paper improves the implementation scheme of baseline interferometric quantum positioning system proposed by Dr. Thomas B. Bahder, U. S. Army Research Laboratory. An improved QPS based on three satellites is proposed to locate users. The number of satellites needed and the complexity of the system is reduced. The whole process of ranging and positioning of the improved satellite-based QPS is analyzed and the system structure is designed. Firstly, a satellite-ground optical link is established between the satellite and the ground. The quantum entangled light emitted by the user equipment and transmits to the satellite along the satellite-ground optical link, and then returns to the user through the reflection of the satellite along the original path. The TDOA of signal light and reference light is obtained by pulse matching counting and data fitting with least square method. Finally, the distance and user space coordinates are calculated according to the TDOA simultaneous equations obtained from entangled light of three satellites. Through the Acquisition Tracking and Pointing (ATP) system to achieve the uninterrupted positioning of the user. The structure of this paper is as follows: Firstly, the flow of the whole system is explained, including the establishment of satellite-ground optical link, the acquisition of TDOA by entangled light, and then ranging and location solution by simultaneous equations. (Bahder, T. B, 2004)

2 BASIC PRINCIPLE OF IMPROVED SATELLITE-BASED QPS LOCATION

The ranging and positioning process of improved satellite-based QPS can be divided into three parts: Firstly, a stable optical link is established between satellites and the earth, and the positioning are carried out by using quantum entangled optical dynamic communication. The establishment of satellite-to-ground optical link is to provide accurate optical links for quantum entangled optical signals to propagate between satellites and users, including beacon light emission, acquisition, tracking and aiming. These four sub-processes are realized by ATP system. Then, based on the quantum entangled light ranging, according to the established satellite-ground optical link, the quantum entangled light dynamic communication is used for ranging and positioning. Its working process is divided into the emission and reception of quantum entangled light and the acquisition of TDOA. Finally, the position is calculated based on the equations obtained by TDOA quantum ranging. (Yang, C, et.al, 2010)

Geometric positioning principle is used in positioning calculation. Two entangled beams of light emitted by the entangled photon pairs generator at the user end, one of which arrives at the satellite along the satellite-ground optical link and reflects back to the ground from the satellite, then received by a single photon detector on the user side; the other light is directly emitted to another single photon detector on the user side to complete the emission and reception of entangled photon pairs. The distance is calculated by using TDOA of two entangled beams. The user's spatial coordinates are calculated by three TDOAs obtained from three satellites.

When the difference of arrival time Δt_nbetween satellite n (n=1, 2, 3) and user is obtained, the distance between satellite and user can be calculated as $D_n = c * \Delta t_n / 2$. Let the space coordinates of three quantum satellites be(x_1, y_1, z_1), (x_2, y_2, z_2), $(x_3, y_3, z_3)$and(x, y, z) respectively. The formula of the relationship between the distance between each satellite and the user and the coordinates of the ground user can be obtained: $D_n = c * \frac{\Delta t_n}{2} = \sqrt{(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2}$. By measuring the arrival time difference of entangled light from the user to three satellites, three formulas of parallel equations are obtained:

$$\begin{cases} c * \frac{\Delta t_1}{2} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2 + (z_1 - z)^2} \\ c * \frac{\Delta t_2}{2} = \sqrt{(x_2 - x)^2 + (y_2 - y)^2 + (z_2 - z)^2} \\ c * \frac{\Delta t_3}{2} = \sqrt{(x_3 - x)^2 + (y_3 - y)^2 + (z_3 - z)^2} \end{cases}$$

The space coordinates (x, y, z) of the ground user are obtained. The improved QPS maintains the satellite-ground optical link between the moving satellite and the user through the advanced aiming module, realizes the uninterrupted positioning of the user.

3 DESIGN OF IMPROVED SATELLITE-BASED QPS

The establishment of satellite-ground optical link is realized by ATP system, as shown in Figure 1. The yellow line represents the path of light propagation and the red line represents the electrical signal. ATP system consists of beacon light module, coarse tracking module, meticulous tracking module and advanced aiming module. The coarse tracking module consists of an optical antenna, a turntable, a coarse tracking detector and a coarse tracking controller. The meticulous tracking module consists of a fast reflector, a meticulous tracking detector and a meticulous tracking controller. (Giovannetti, V, et.al, 2003)

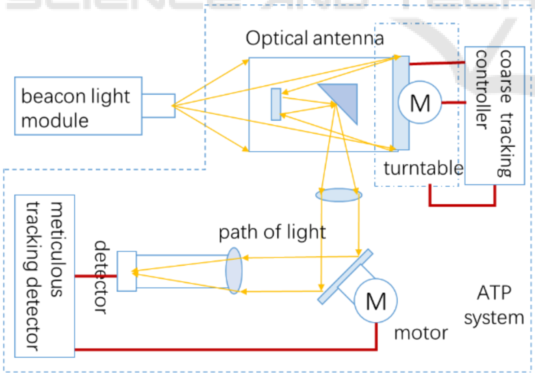

Figure 1. ATP system schematic diagram.

Satellite terminal and ground terminal transmit beacon light to each other through their beacon light module, and use ATP system to capture, track and aim beacon signal, establish a two-way aiming satellite-ground light link. Firstly, the satellite end acts as the emitter of beacon light and the ground end acts as the capturer. Based on ephemeris information, the orbit and time period of the satellite passing over the ground are calculated at the ground end, and then the turntable in the coarse tracking module is rotated to point its line of sight to the uncertain region of the satellite passing over the user. Subsequently, the optical antenna at the satellite scans the uncertain area where the user is located, searches for the beacon light emitted by the user, realizes rough tracking, and acquisition process. In the precise tracking stage, FSM first reflects the up-going beacon light which is output by an optical antenna and processed by a collimating lens, then enters the precise tracking detector through the precise tracking lens of the detector, and forms a spot on the detector. The precise tracking controller calculates the output control signal through a certain control algorithm and controls the FSM to deflect at a certain angle, so that the beacon light can accurately track the detector center and achieve the precise alignment of the incident optical axis and the optical axis of the main optical antenna. At this point, the satellite terminal and the ground terminal are in the tracking state. When two-way tracking is completed at both ends of the satellite and the user, the establishment and maintenance of the satellite-ground optical link can be realized, and the emission and reception of quantum entangled light can be carried out in the next step. (Cahill, R. T, 2003)

On the established precisely aligned satellite-ground optical link, ranging based on quantum entangled light is the key to the whole QPS. The TDOA acquisition process for a set of improved QPS is shown in Figure 2. The yellow line represents quantum entangled beam, and the red line represents electrical signal. The process is mainly completed by four parts: entangled photon pair generator, ATP system, single photon detector and data processing unit. (Liao, S. K, et.al, 2017)

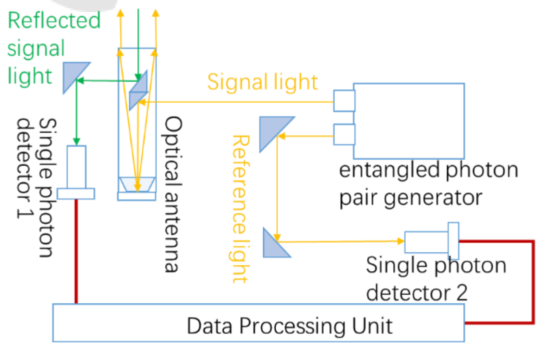

Figure 2. The TDOA acquisition process of the improved QPS.

After the satellite-ground optical link is established, the user end begins to transmit and receive quantum entangled light. The entangled photon pair generator produces correlated signal light and reference light, in which the signal light is incident to the advanced sighting mirror. The advanced sighting module drives the advanced sighting mirror to adjust an angle by calculating the instantaneous angle deviation caused by the relative motion of the satellite and the ground, so as to compensate the angle deviation of the signal light. Then the signal light enters the FSM of the precise tracking module, and reflects it to the mirror of the coarse tracking module, and then to the optical antenna, which transmits the signal light to the cone reflector at the satellite end. The signal light of entangled photon pair passes through the ground corner cone reflector and returns to the ground-end ATP system along the original path. First, through the optical antenna to enters the mirror of the coarse tracking module and reflects to the FSM of the meticulous tracking module, and then incident to the single photon detector 1. After emitted by the entangled photon pair generator, the reference light reflected by the mirror, and be directly received into the single photon detector 2. (Thon, S. M, et.al, 2009)

4 POSITIONING SOLUTION AND SIMULATION OF IMPROVED STAR-BASED QPS

The time difference between the time1 when the signal light reaches the detector 1 and the time2 when the reference light reaches the detector 2 is called the arrival time difference Δt. And multiplying it by the speed of light to obtain the optical path difference between the signal light and the reference light, and calculating the distance between the satellite and the ground user. This paper proposes a pulse matching count and data fitting process to obtain the arrival time difference. The whole process is shown in Figure 3:

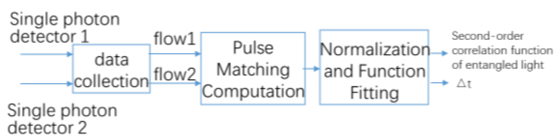

Figure 3. Pulse matching measurement process.

A pulse matching count is performed with flow1 by adding different delay values ΔT to the signal of flow2. When the delay value of flow2 ΔT is equal to Δt, all the pulses on flow1 and flow2 can be matched, and the matched pulse value reaches the maximum. Since the second-order correlation function of the entangled light corresponds to the relationship between the counting value and the time delay, the delay ΔT corresponding to its maximum value is the delayed value Δt of the entangled light. According to the corresponding matching counts obtained by given different delays ΔT, the matching counts are normalized, and then drawn the discrete point curve. By fitting the value of the second-order correlation function of the discrete entangled light obtained by normalization, it is found that the corresponding ΔT of the maximum value of the function is the actual arrival time difference Δt of the entangled light.

Figure 4 is a second-order correlation function curve of the entangled light obtained by pulse matching counting at delay time ΔT, where the red point is a normalized discrete sample point, green line is the fitted second-order correlation function curve, and the blue line corresponds to the peak point coordinate of the fitted curve. The entangled light Δt obtained by the curve is $0.482347 \times 10^{-3} S$. (Takenaka, H, et.al, 2017)

5 FIGURE 4 SECOND-ORDER CORRELATION FUCTION CURVE

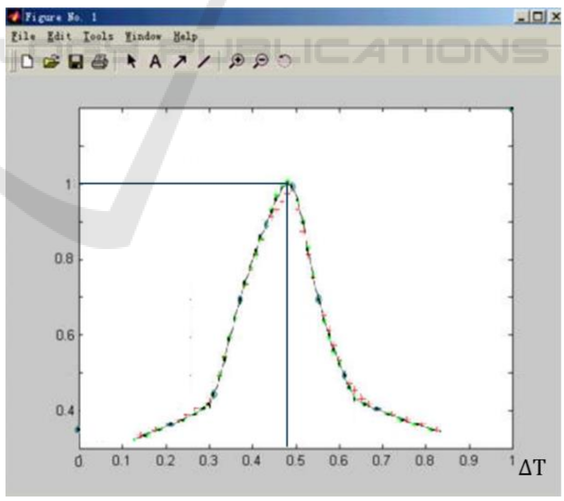

Figure 4. Second-order correlation function curve of entangled light at different ΔT.

6 CONCLUSION

In this paper, an improved star-based QPS system is proposed and systematically described. The whole

QPS system includes: the establishment of the star-ground optical link, the acquisition of TDOA of the entangled light, the ranging and positioning solution process. Compared to the traditional 3-baseline star-based QPS system, the number of satellites required is effectively reduced.

REFERENCES

Bahder, T. B. (2004). Quantum positioning system. Physics.

Cahill, R. T. (2003). Quantum-Foam In-Flow Theory of Gravity and the Global Positioning System (GPS). arXiv preprint physics/0309016.

Giovannetti, V, Lloyd, S, & Maccone, L. (2001). Quantum-enhanced positioning and clock synchronization. Nature, 412(6845), 417-419.

Giovannetti, V., Lloyd, S., & Maccone, L. (2003). Quantum positioning system. In Coherence and Quantum Optics VIII (pp. 303-304). Springer, Boston, MA.

Giovannetti, & V. (2004). Quantum-enhanced measurements: beating the standard quantum limit. Science, 306(5700), 1330-1336.

Liao, S. K., Cai, W. Q., Liu, W. Y., Zhang, L., Li, Y., Ren, J. G., ... & Li, F. Z. (2017). Satellite-to-ground quantum key distribution. Nature, 549(7670), 43.

Marks, & Paul. (2014). Quantum positioning system steps in when gps fails. New Scientist, 222(2969), 19.

Takenaka, H., Carrasco-Casado, A., Fujiwara, M., Kitamura, M., Sasaki, M., & Toyoshima, M. (2017). Satellite-to-ground quantum-limited communication using a 50-kg-class microsatellite. Nature photonics, 11(8), 502.

Thon, S. M., Rakher, M. T., Kim, H., Gudat, J., Irvine, W. T., Petroff, P. M., & Bouwmeester, D. (2009). Strong coupling through optical positioning of a quantum dot in a photonic crystal cavity. Applied Physics Letters, 94(11), 111115.

Yang, C., Wu, D., & Yu, Y. (2010). The Integration of GPS and Interferometric Quantum Position System for High Dynamic Precise Positioning. IEEE.