Research of Satellite and Ground Time Synchronization Based on a New Navigation System

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Abstract The new navigation time synchronization method is a breakthrough in existing navigation systems time synchronization accuracy limit, and it is an effective way to reduce system construction costs. By placing more accurate atomic clock in GEO satellites, it can synchronize with ground systems and generate time reference, the GEO satellites can give time to other navigation satellites, the new system can achieve high-precision time synchronization. This paper designs the navigation constellation of the new satellite navigation system, and configures the satellite clocks, simulates all kinds of constellation time synchronization precision, and educes the satellite clock configure scheme in the new navigation system.

Keywords Navigation system · Time synchronization · Satellite clock

1 Introduction

Satellite navigation systems have been widely used in military and civilian aspects of various countries and have achieved great benefits. But still there are various disadvantages in navigation system, as the number of existing satellite onboard atomic clocks demands more and high costs [1, 2]. Therefore, the use of new atomic clock design, to explore new satellite clock configuration is an effective way to reduce system construction costs.

The new time synchronization method is essentially a kind of satellite-ground, inter-satellite system operation control concept: it contains GEO satellites constellation and high accurate atomic clock; its time reference is generated by the GEO satellites and the system Control Segment Operational; it mainly relies on the OCS to do the centralized satellite-ground and inter-satellite measurement

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processing; it depends on the inter-satellite link to update the ephemeris, and to shorten the data age. So, non-GEO satellite of the navigation constellation can use reasonable algorithm, high-precision satellite-ground and inter-satellite link, and the configuration of the ultra-stable crystal oscillator, to achieve a high precision with low construction cost.

2 The New Time Synchronization Plan

Under the new system time synchronization plan involved basic navigation constellations and star clock design, the link design, and time synchronization plan.

This system needs GEO satellite to provide time service, so the constellation must contain GEO satellites. For new time synchronization system, GEO satellites use more accurate onboard atomic clock which builds a time reference together with the OCS clock [3]. This paper takes two types of optical clocks and hydrogen atomic clock as a time reference installed on the GEO satellite, and non-GEO satellites use ordinary onboard atomic clock or ultra-stable crystal oscillator. The new time synchronization system involves satellite-ground link and inter-satellite link. Inter-satellite link contains timing link between GEO and non-GEO satellite and time synchronization link between non-GEO satellites. The new time synchronization method contains that: non-GEO satellites-ground link use satellite time and frequency transfer method; inter-satellite link use inter-satellite two-way time and frequency transfer method; GEO satellite-ground link use both satellite laser ranging and two-way time and frequency transfer method; OCS and each time synchronization stations use both satellite two-way time and frequency method and satellite common-view method.

3 Time Synchronization Measurement Model

The satellite-ground microwave observation model can be expressed as [4]:

$$\rho' = \rho + c \cdot (\Delta t_S - \Delta t_R) + \Delta\rho_{\text{ion}} + \Delta\rho_{\text{tro}} + \Delta\rho_{\text{rel}} + \Delta\rho_{\text{scc}} + \Delta\rho_{\text{ant}} + \Delta\rho_{\text{ml}} + \varepsilon \quad (1)$$

In this formula, ρ' is microwave observation value, ρ is the true distance from the ground station to the satellite; c is the light speed, Δt_S is satellite clock error, and Δt_R is ground station clock error; $\Delta\rho_{\text{ion}}$ is ionospheric delay error, $\Delta\rho_{\text{tro}}$ is tropospheric delay error; $\Delta\rho_{\text{rel}}$ is relative delay error; $\Delta\rho_{\text{scc}}$ is satellite centroid compensation correction; $\Delta\rho_{\text{ant}}$ is antenna phase center error; $\Delta\rho_{\text{ml}}$ is multipath effect; ε is pseudo range observation noise.

The satellite-ground laser observation model

The observation model of the satellite-ground laser ranging can be expressed as:

$$\rho' = \rho + \Delta\rho_{\text{tro}} + \Delta\rho_{\text{rel}} + \Delta\rho_{\text{scc}} + \Delta\rho_{\text{ec}} + \Delta\rho_{\text{ant}} + \Delta\rho_{\text{ml}} + \varepsilon \tag{2}$$

In this formula, ρ' is laser observation value. ρ is the true distance from the laser station to the satellite; $\Delta\rho_{\text{tro}}$ is tropospheric delay error; $\Delta\rho_{\text{rel}}$ is relative delay error; $\Delta\rho_{\text{scc}}$ satellite centroid compensation correction; $\Delta\rho_{\text{ec}}$ is station coordinate correction; $\Delta\rho_{\text{ant}}$ is antenna phase center error; $\Delta\rho_{\text{ml}}$ is multipath effect; ε is laser observation noise.

Two-way measurement equation

The two-way measurement equation can be obtained from the single direction measurement equation of satellite-ground and inter-satellite.

$$\begin{cases} \bar{\rho}_{ij} = d + c \cdot \delta t_i - c \cdot \delta t_j + n_{ij} \\ \bar{\rho}_{ji} = d + c \cdot \delta t_j - c \cdot \delta t_i + n_{ji} \end{cases} \tag{3}$$

In this formula, $\bar{\rho}_{ij}$ and n_{ij} are pseudorange (microwave, laser) and measurement noise from point S_i to S_j; $\bar{\rho}_{ji}$ and n_{ji} are corrected pseudorange (microwave, laser) and measurement noise from satellite S_i to S_j; δt_i and δt_j are clock error S_i and S_j. c is the light speed and d stands for distance between S_i and S_j, as below: $d = [(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]^{1/2}$.

4 Satellite Clock Modeling and Time Synchronization Algorithm

The atomic clock used in the satellite navigation system contains system change and random error. Atomic clock error may be expressed as the difference between the instantaneous clock time and the standard time $x(t)$. Choose quadratic polynomial model as clock error model

$$x(t) = a_0 + a_1(t - t_0) + \frac{1}{2}a_2(t - t_0)^2 + \varepsilon_x(t) \tag{4}$$

In this formula, a_0 is the initial phase(time) deviation, a_1 is the initial deviation of the atomic clock frequency, and a_2 is linear frequency drift rate; $\varepsilon_x(t)$ is the random variation component of clock deviation caused by clock noise; t_0 is the reference time. The step of time synchronization process is as follows: observation data pretreatment, parameters priori information determination, initial clock error calculation, time estimation matrix building, residual edit, and iteration [5].

5 Simulation and Results Analysis

5.1 Atomic Clock and Clock Data Simulation

Allan variance is the most common expression of frequency stability, which depends on the length of time stability, and is divided into short-term frequency and long-term stability. Although the definition of short-term stability and long-term frequency stability is same, they reflect different aspects of signal stability characteristics. Measurement of short-term frequency stability in the time domain is very difficult, or even impossible, but at the same time it is easier to measure in the frequency domain. So, short-term frequency stability measurement can be converted into a time domain phase noise, so as to get the short-term time domain stability indirectly. Phase noise theory and statistical thin phase noise of time domain and frequency domain Allan variance are equivalent. If got the conversion relationship between them, the amount of each physical characterization can be then revealed. This paper use Allan variance as the satellite clock error calculation model.

When calculating the simulation, noise as above is generated by the white noise, and relevant noise generation process is as follows [6]:

$$y_i^{\mathrm{WP}} = \sigma_{y\mathrm{WP}}(\tau) \cdot (\mathrm{rand}_i - \mathrm{rand}_{i-1}) y_i^{\mathrm{WF}} = \sigma_{y\mathrm{WF}}(\tau) \cdot \sqrt{3} \cdot \mathrm{rand}_i$$
$$y_i^{\mathrm{RW}} = y_{i-1}^{\mathrm{RW}} + \sigma_{y\mathrm{RW}}(\tau) \cdot 3 \cdot \mathrm{rand}_i$$
$$y_i^{\mathrm{FF}} = \sigma_{y\mathrm{FF}}(\tau) \cdot \sqrt{5} \cdot [i^{-2/3}\mathrm{rand}_1 + (i-1)^{-2/3}\mathrm{rand}_2 + (i-2)^{-2/3}\mathrm{rand}_3 + \cdots + \mathrm{rand}_i]$$

In this formula, $\mathrm{rand}_i \sim N(0,1)$, N is the number of sampling points.

Atomic clock error is calculated by the following formula:

$$x_i = x_{i-1} + \tau(y_i^{\mathrm{WP}} + y_i^{\mathrm{WF}} + y_i^{\mathrm{FF}} + y_i^{\mathrm{RW}}) \quad i = 1, 2, \ldots N \tag{5}$$

5.2 Simulation of Ultra-Stable Oscillator Data

Crystal error is more complex, so there is no proper mathematical model yet. Since there is no direct ultra-stable oscillator laboratory results, this paper uses Allan variance provided by ACES. Inverse the main Allan variance noise component, and put them together (Table 1).

Table 1 ACES ultra-stable crystal oscillator (USO) Allan variance with interval

Measurement interval (s)	1	2	4	10	20
Sigma	1.49e−13	1.26e−13	1.00e−13	8.82e−14	8.88e−14
Interval (s)	40	100	200	400	1000
Sigma	9.67e−14	1.23e−13	1.30e−13	1.20e−13	2.25 e−13

Table 2 Calculated Allan variance of noise figure

h_{-2}	h_{-1}	h_0	h_1	h_2
1.00e−13	8.82e−14	8.88e−14	9.67e−14	1.23e−13

With the condition of knowing Allan variance value of five typical time interval τ, h_{-2}, h_{-1}, h_0, h_1, h_2 can be calculated; knowing more than five Allan variance value, it can be calculated by least squares method, and then calculate any corresponding Allan variance (Table 2).

Because the random walk, frequency flicker noise, frequency white noise, flicker phase noise, and phase noise are independent random processes, after separated apart, five noises can use its own characteristic to inverse error sequences.

You can utilize these five separate noises respective characteristics, separated these noises and inversion error sequence, the formula shows in Eq. (5).

5.3 Simulation Conditions

In this paper, navigation constellation consists of MEO, GEO, and IGSO numbered 1–35, of which No. 1–27 is MEO satellites, No. 28–30 is IGSO satellite, and No. 31–35 is GEO satellite. Inter-satellite link error is set to 0.1 m (1σ). Satellite-ground link error is analyzed in two ways: Microwave satellite-ground microwave link error is 1.2 m (1σ); Laser microwave link error is 0.1 m (1σ).

There are five domestic time synchronization stations, whose minimum elevation observations are 5°. The simulation period is 7 days. Onboard satellite clock error, initial onboard clock error σ_{X_0}, and covariance matrix P_{X_0} of hydrogen maser, rubidium and cesium clock, optical clocks, ultra-stable oscillator is as [7, 8].

The simulation program is in Table 3.

Table 3 Simulation algorithm design

Scenario	Station	GEO	Non-GEO	Measurement
I	Hydrogen	Cesium	Rubidium/Cesium	Microwave satellite-ground link + Ka inter-satellite links
II	Optical	Optical	Rubidium + Cesium	Microwave satellite-ground link + Ka inter-satellite links
III	Optical	Optical	Ultra-stable oscillator	Microwave and laser joint satellite-ground link + Ka inter-satellite link
IV	Optical	Hydrogen	Rubidium + Cesium	Microwave and laser joint satellite-ground link + Ka inter-satellite link
V	Optical	Hydrogen	Ultra-stable oscillator	Microwave and laser joint satellite-ground link + Ka inter-satellite link

5.4 Simulation Results Analysis

Figures 1 and 2 are traditional satellite time synchronization error statistics. Without navigation constellation two-way filtering time synchronization, or entire constellation drift time, which maximum drift is about 7 ns, the introduction of inter-satellite links increased redundancy observations to help improve the time synchronization accuracy, to keep constellation drift within 0.65 ns in simulation conditions.

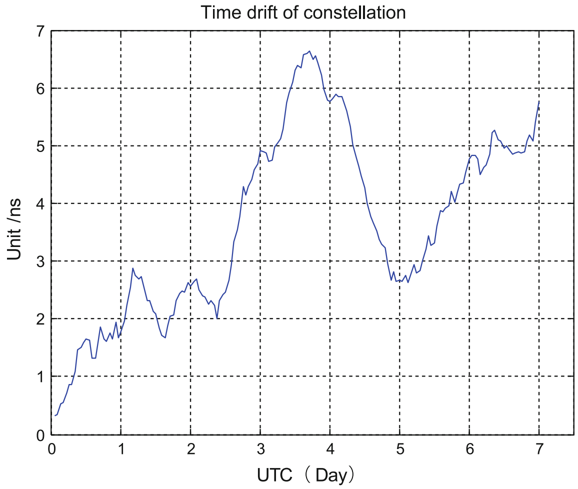

Fig. 1 Option I: constellation time drift error

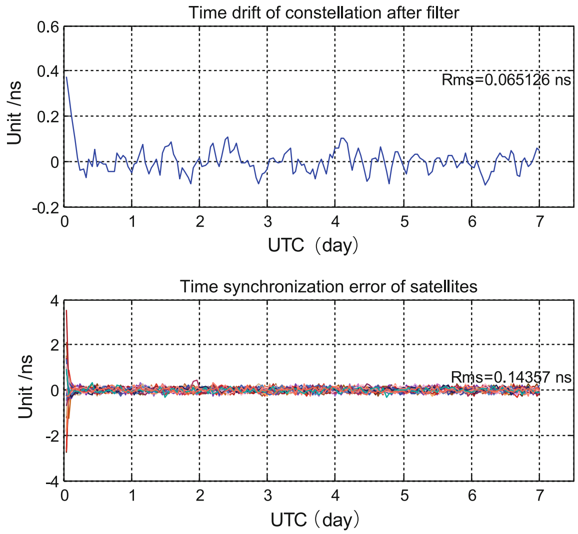

Fig. 2 Option I: constellation drift and satellite time synchronization error

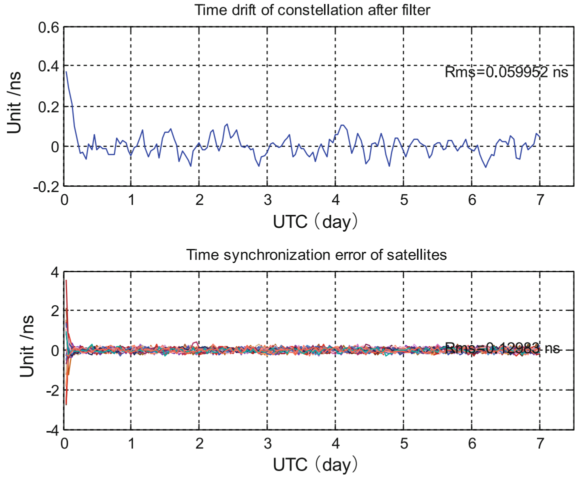

Fig. 3 Option II: constellation drift and satellite time synchronization error

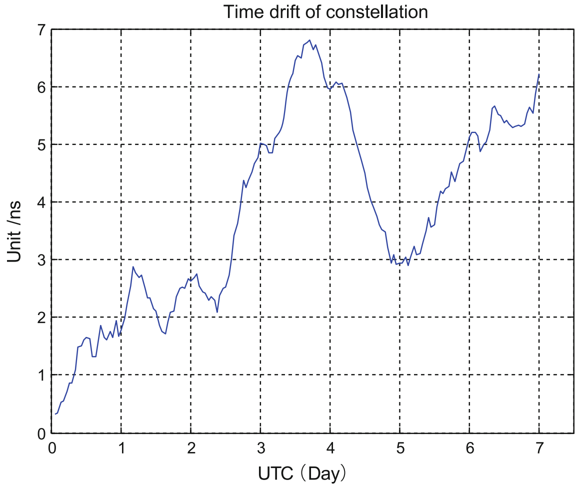

Fig. 4 Option II: constellation time drift error

Figures 3 and 4 are atomic clock + atomic clock(rubidium, cesium). Due to the GEO satellite uses a high-precision optical clocks, the simulation use laser and microwave joint satellite-ground link to take place traditional satellite-ground link; the clock of ground station is optical clock; GEO equipped with optical atomic clock; GEO onboard clock does not participate in time synchronization between non-GEO satellites, and only do time synchronization with ground stations to keep time reference. The time reference in this paper is time reference in navigation system with respect to UTC, not taking the establishment of optical clocks to improve the accuracy of UTC time in consideration. Figure 3 shows that the average constellation time (the constellation drift) and constellations time synchronization accuracy with respect to the traditional model has greatly improved.

At a given simulation conditions, the constellation average time is below 0.06 ns, time synchronization accuracy is below 0.14 ns, non-filtering time synchronization under the same conditions as a whole constellation of synchronization drift reached 7 ns (Fig. 4).

Figures 5 and 6 are the time synchronization accuracy of new optical atomic clock + ultra-stable oscillator clock. Ultra-stable oscillator has a good short-term stability but a poor long stability. Without two-way time synchronization, the whole constellation time shift is about 140 ns (Fig. 6), much larger than the drift of rubidium and cesium clock (Fig. 4). However, when added microwave and laser joint satellite-ground link, the average constellation time (the constellation drift) accuracy is about 0.0488 ns (Fig. 5). Which is slightly better than optical II.

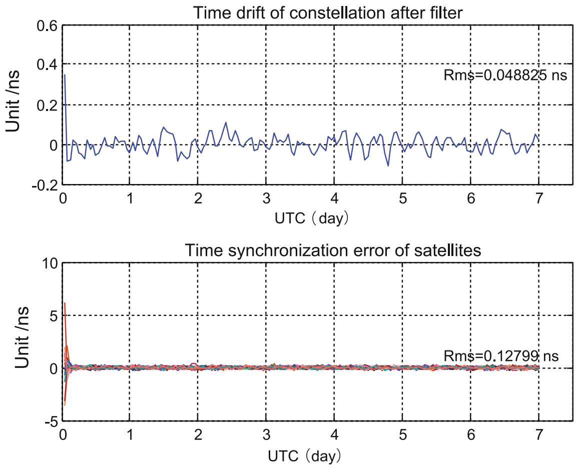

Fig. 5 Option III: constellation drift and satellite time synchronization error

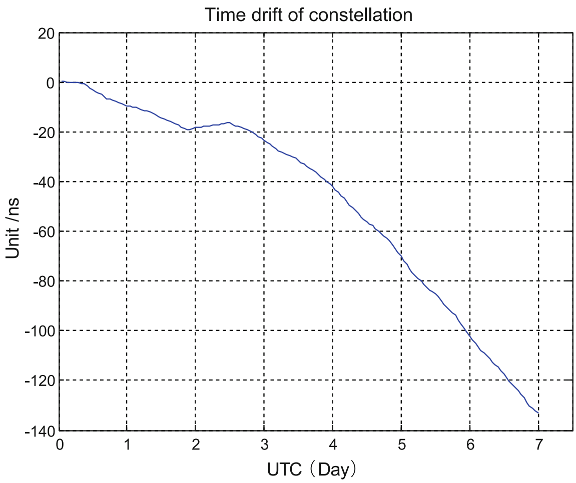

Fig. 6 Option III: constellation time drift error

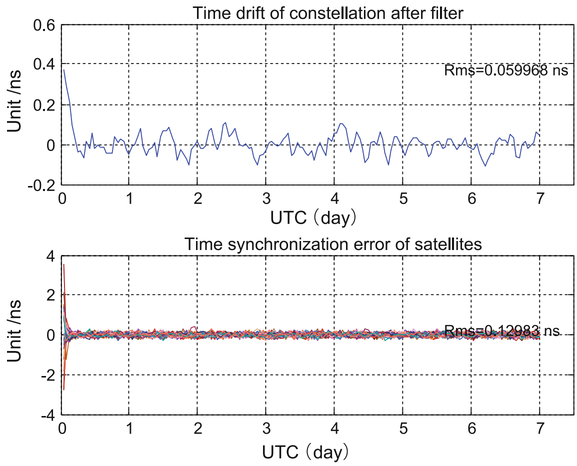

Fig. 7 Option IV: constellation drift and satellite time synchronization error

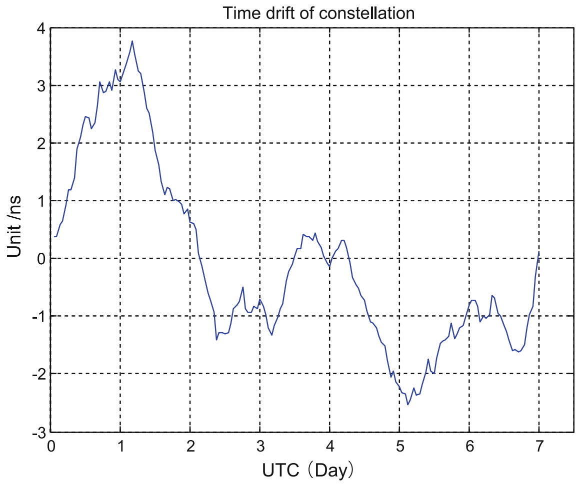

Fig. 8 Option IV: constellation time drift error

Figures 7 and 8 are the time synchronization accuracy of new hydrogen atomic clock + atomic clock(rubidium, cesium). As can be seen from Fig. 7, the average constellation two-way filtering time accuracy is 0.06 ns, time synchronization accuracy is 0.13 ns, and the average two-way filtering time is considerable with option II and III. The time synchronization accuracy of each satellite is lower than option II and III (Fig. 8).

Figures 9 and 10 are the time synchronization accuracy of new hydrogen atomic clock + ultra-stable oscillator clock. GEO is equipped with hydrogen atomic clock; other satellite clock uses ultra-stable oscillator clock. It can be concluded that the overall constellation time drift is about 0.05 ns, time synchronization accuracy is 0.128 ns (Fig. 9). Under the given simulation condition, the accuracy is slightly

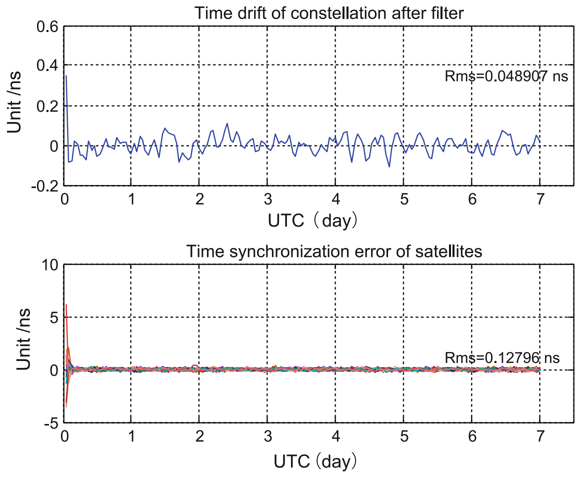

Fig. 9 Option V: constellation drift and satellite time synchronization error

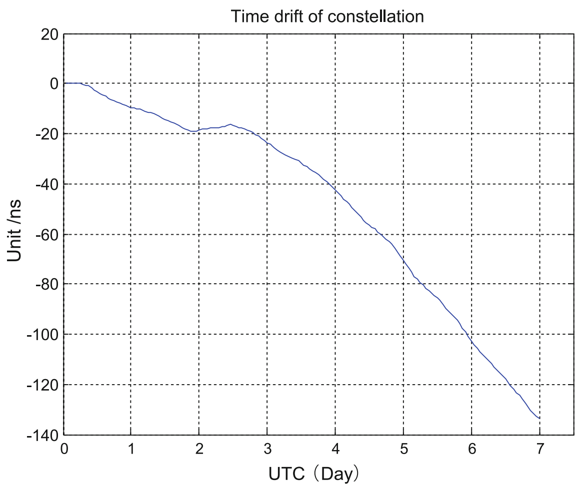

Fig. 10 Option V: constellation time drift error

better than option IV (Fig. 10). The time synchronization accuracy is slightly better than the option IV too.

5.5 *In Conclusion*

The present problem of onboard atomic clock frequency drift, accuracy will be getting worse with time. In this paper, simulation results show that:

The new time synchronization method can greatly improve the time synchronization accuracy.

In the new satellite and ground joint batch processing mode, the accuracy of hydrogen atomic clock and atomic clock on the GEO satellite is at the same orders of magnitude. This is because: when the satellite and ground joint estimation, all observations is transform to the same epoch, and the overall network adjustment make full use of observation information, in order to improve time synchronization accuracy. When the satellite and ground joint estimation, time synchronization accuracy depends on the satellite, the inter-satellite link precision, and algorithms. When GEO is equipped with optical atomic clock, its stability is about 1.25×10^{-12} s, the stability of hydrogenatomic clock is about 6.25×10^{-11}. In the simulation, the satellite-ground link accuracy is about 0.1 m, and the time synchronization error is about 3×10^{-10} s, the noise of satellite-ground link drowned GEO onboard clock performance, so with respect of satellite and ground joint entire network time synchronization, the accuracy of optical atomic clock and hydrogen atomic clock on the GEO satellite is at the same orders of magnitude.

Under the condition of new method, the ultra-stable oscillator can replace rubidium, cesium clock as onboard atomic clock of non-GEO satellites.

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