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Research Article

An Aerospace Layering Time Synchronization Architecture and Intersatellite Microwave Links Performance Analysis Based on 3-Layer Satellite Networks

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Abstract: The appropriate high-accuracy time and frequency standard is basic to normal operation of various kinds of aerospace application systems, which influences systems performance. The study of establishing suitable time and frequency standard and intersatellite performance analysis in aerospace is very important. Based on the establishment of aerospace satellite visual model, the simulation of satellite visual time on 3-layer satellite networks, including GEO satellite (Geostationary Earth Orbit), IGSO (Inclined Geosynchronous Orbit) satellites and MEO (Medium Earth Orbit) satellites, has been conducted. The visual features of this satellite network have been gained. Combining with the major influencing factors of satellite clock correction error, aerospace time synchronization architecture on the basis of layering has been proposed. Furthermore, intersatellite links performance analysis is the basis for establishing aerospace layering time synchronization architecture. The 3-layer satellite networks is used as an example to simulate the variation range of distance interlayer satellites of the 3-layer satellite networks and to analyze the performance of GEO-IGSO, GEO-MEO and IGSO-MEO links in S-band and Ka-band under the preset intersatellite transmission system, link parameters, transmission loss and without regard to the error of the intersatellite pointing accuracy. The results show that at the maximum intersatellite distance, if the S-band transmission rate is in excess of 2 Mbps, when the antenna is 1 m in diameter, the transmitting power needed is about 50 W. In the Ka-band, 1m antennas only need 1 W transmitting power to provide an intersatellite data transmission rate higher than 2 Mbps. The Ka-band is more favorable for improving the performance of intersatellite links of 3-layer satellite networks. Research results serves as reference for the establishment of aerospace layering time synchronization architecture based on 3-layer satellite networks.

Keywords: Intersatellite communication, links performance analysis, satellite networks, time synchronization architecture

INTRODUCTION

With the rapid development of aerospace technology, space application has taken on various forms, with satellite navigation system, space-based measurement and control, manned space flight, deep space exploration and distributed satellite system as their typical representatives. In order to realize the comprehensive utilization of aerospace information, the construction of space-based comprehensive information networks is proposed. Aerospace integration is becoming a basic trend of development in the field of aerospace (Wang, 2007; Dai and Lu, 2004). How to realize time synchronization between all spacecrafts, between spacecrafts and ground facilities and how to allow all systems to conduct cooperative work under the unified time will be major issues to be solved in the process of aerospace integration.

In the current aerospace application, as the time reference is established on the ground, most of spacecrafts for the aerospace technological activities have to conduct time synchronization with their own ground station independently. This method will be affected by short synchronization time and low synchronization accuracy. Furthermore, under unusual circumstances, once the ground station is been destroyed, the whole system will be in danger of falling into paralysis. However, the establishment of high-accuracy time frequency standard in aerospace will solve the problem effectively. The present researches about space-based comprehensive information network mainly focus on satellite network system structure (Bai

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et al., 2006; Lee *et al*., 2000), space information transmission model (Ding, 2007), intersatellite link performance design and simulation (Wang *et al*., 2004), routing algorithm of multi-layer satellite network (Yi *et al*., 2007; Bai *et al*., 2004). There are few researches on establishment of aerospace high-accuracy time frequency standard, on aerospace time synchronization architecture and on time synchronization link performance analysis.

On the basis of simulation of satellite visible time and the variation range of the intersatellite link distance of the 3-layer satellite networks, this study presents a new aerospace layering time synchronization architecture, analyzes the interlayer links performance in S-band and Ka-band of the aerospace layering time synchronization architecture.

SATELLITE VISUAL MODELING AND SIMULATION OF THREE-LAYER SATELLITE NETWORKS

The three-layer satellite networks are composed of GEO, IGSO and MEO satellites. They form the GEO satellites layer, IGSO satellites layer and MEO satellites layer (Huang *et al*., 2012b). Among them, GEO satellites layer and IGSO satellites layer have three satellites and MEO satellites layer has seven satellites. The realization of time synchronization among satellites depends on the following two aspects: for one thing, physical visibility has to be achieved between satellites; for another, on the basis of physical visibility, requirements on electromagnetic wave power for the normal communication have to be met. This study conducts researches on establishment of aerospace layering time synchronization architecture by 3-layer satellite networks. As a result of this, the visible time of satellites, meaning the time span of synchronization, has to be considered.

Satellite mutual visual model: For those two earth-around-rotating satellites, after the determination on locations of satellites at any time in the space, they can only achieve visibility when they are both above the same plane which is tangent to the earth surface. The extreme situation is that both of them are in the tangent plane. Therefore, the visibility function to describe that whether these two satellites can achieve visibility is gained. The function is as follows (Zhang and Zhang, 2001):

$$\psi = \alpha_1 + \alpha_2 - \phi \tag{1}$$

When $\Psi>0$, the two satellites can achieve visibility. Otherwise, there is no visibility.

Visual time simulation of three-layer satellite networks: Based on the above satellite mutual visible models, the simulations of four typical visible situations in 3-layer satellite networks have been done with the help of satellite simulation tool software STK (Satellite Tool Kit). The results are as follows: the continuous 24 h visibility is possible between GEO satellites and between GEO satellites layer and IGSO satellites layer. The minimum visual time between GEO satellites layer and MEO satellites layer takes 97.47% of the whole MEO satellites simulation cycle, meaning in the whole simulation cycle, GEO satellites layer and MEO satellites layer can achieve visibility in 97.47% of the time. IGSO satellites layer and MEO satellites layer can have mutual visibility in 98.55% of the total simulation cycle (Huang *et al*., 2012b).

Design of aerospace layering time synchronization architecture: When every satellite in 3-layer satellite networks has loaded atomic clock, clock correction error of satellite is comprised of clock correction parameters measurement error and extrapolation error. Under the condition that frequency stability of satellite clock cannot be guaranteed, the length of extrapolation time of satellite clock correction will seriously affect the accuracy of clock correction of satellite clock. Satellite clock correction extrapolation model is normally the second-order polynomial about time (Shi and Zhao, 2007):

$$\Delta t = a_0 + a_1(t - t_{oc}) + a_2(t - t_{oc})^2 \tag{2}$$

In the polynomial, Δt is satellite clock correction, t_{oc} is starting point reference time of model and a_0, a_1 and a_2 are respectively phase deviation of satellite clock relative to standard time (clock correction), frequency deviation of clock relative to actual frequency (clock rate) and frequency drift of clock (change rate of clock rate, drift). In it, error of quadratic item (or high order term) coefficient is mainly represented by frequency stability. Unstable clock will cause high fitting error which influence will drastically increase with the length of extrapolation time. When the satellite clock has bad frequency stability, the shorter extrapolation time will give rise to higher accuracy of extrapolation satellite clock correction (Xu, 2001). On the basis of normal inter-satellite communication required by inter-satellite linking antenna tracking direction and satellite transmitting power, the length of synchronization time among satellites will also have great influence on the accuracy of satellite clock correction.

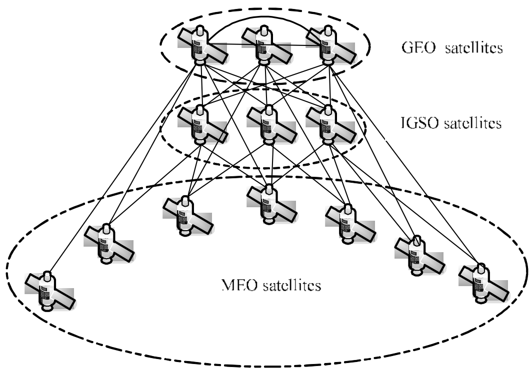


Fig. 1: Schematic diagram of aerospace layering time synchronization architecture

According to the comparison of visual time simulation results on 3-layer satellite networks, layering time synchronization architecture, with the GEO satellites as the time synchronization source of 3-layer satellite constellation, can be established. In this architecture, GEO satellites realizes intersatellite time synchronization with IGSO satellites and MEO satellites with the establishment of intersatellite link, increasing the time length of synchronization of IGSO satellites and MEO satellites in the whole operation cycle, decreasing clock correction extrapolation time of IGSO satellites and MEO satellites, boosting time synchronization accuracy of IGSO satellites and MEO satellites. The system realizes high accuracy time synchronization among GEO satellites; based on this, system achieves high accuracy time synchronization with GEO satellites and IGSO satellites; at last, both of the satellites conduct high accuracy time synchronization with MEO satellites, really implementing GEO satellites, IGSO satellites and MEO satellites time synchronization. Eventually, accurate aerospace system time frequency standard could be established by 3-layer satellite networks. By taking advantage of this system time frequency standard, high-accurate time service could be provided to all aerospace application systems. The schematic diagram of time synchronization architecture is shown in Fig. 1 (Huang *et al.*, 2012a). In the diagram, line or curve represent intersatellite time synchronization links.

SIMULATION OF THE VARIATION RANGE OF INTERSATELLITE LINK DISTANCE OF THE 3-LAYER SATELLITE NETWORKS

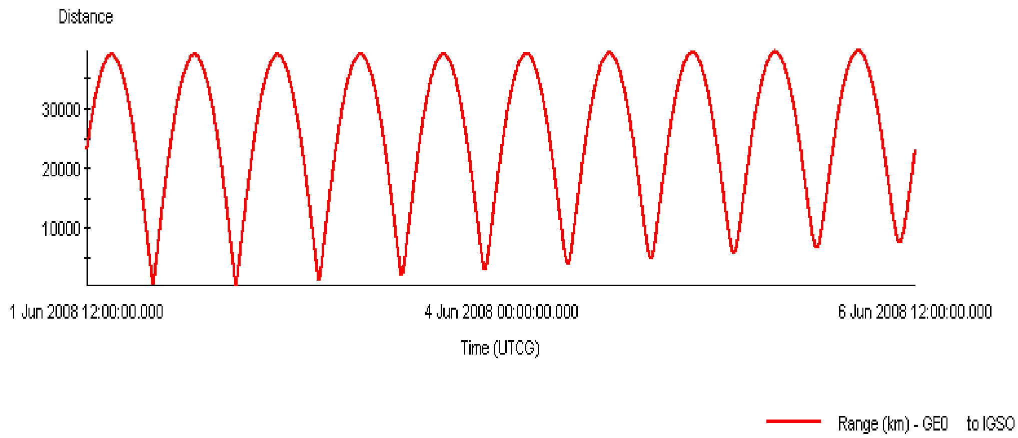
Main parameters of performance analysis of intersatellite links: An intersatellite link can be considered as a special wave beam of a multi-beam antenna. This wave beam does not point at the earth's surface but rather at other satellites. Intersatellite links include those between satellites of the same orbit altitude and those between satellites of different orbit altitudes. Intersatellite links between satellites of the same orbit altitude can be further divided into intra-orbit intersatellite links within the same orbit plane and inter-orbit intersatellite links within different orbit planes. The azimuthally angle, elevation and intersatellite distance between two satellites having intersatellite links are usually subject to variations with time. Variations of the azimuthally angle and elevation require the automatic tracking capability of the satellite antennas. Variation of the link distance requires the automatic power control capability of the antennas. Therefore parameters determining the difficulty of the establishment of intersatellite links of a satellite network include dynamic variation ranges and rates of azimuthally angle, elevation and intersatellite links distance (Liu, 2004). This study is focused on the analysis of the communication performance of intersatellite links established between different layers of the 3-layer satellite networks. Therefore the variation range of intersatellite distance is one of the main parameters for the performance analysis of intersatellite links.

Simulation of the variation range of intersatellite links distance of the 3-layer satellite networks: In order to obtain the rules of the variation of distances of interlayer links of the 3-layer satellite networks, an simulation tool STK (Satellite Tool Kit) is used to simulate the variation of intersatellite distance within the 3-layer satellite networks. Figure 2 shows the simulation results.

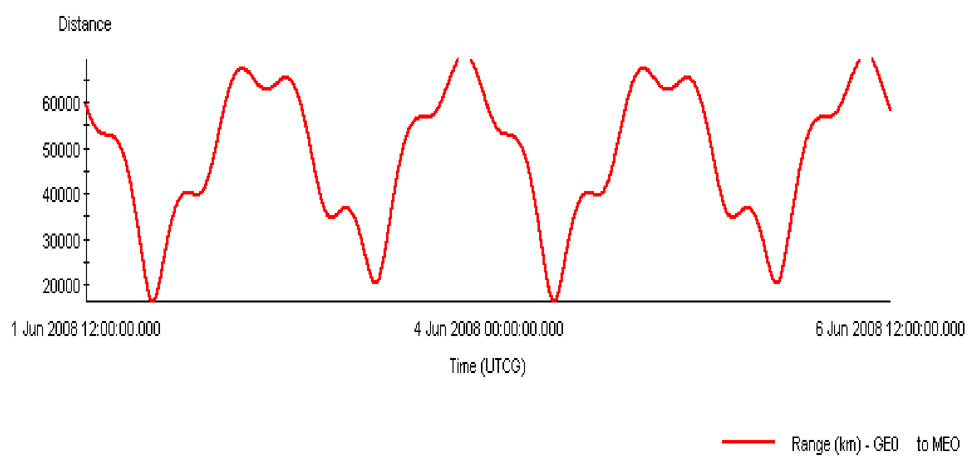
From Fig. 2 we can sum up the following rules of the variation of intersatellite links distance between moving satellites within the 3-layer satellite networks: with the motion of satellites, the intersatellite links distance decreases and increases for many times within a wide range of variation, which has brought certain difficulties to the establishment of intersatellite links.

For the purpose of analysis and comparison the communication performance of intersatellite links of the 3-layer satellite networks within various frequency bands, the specific variation ranges of three typical intersatellite links of the given 3-layer satellite networks are simulated. Table 1 sum up the simulation results (Huang *et al.*, 2012b).

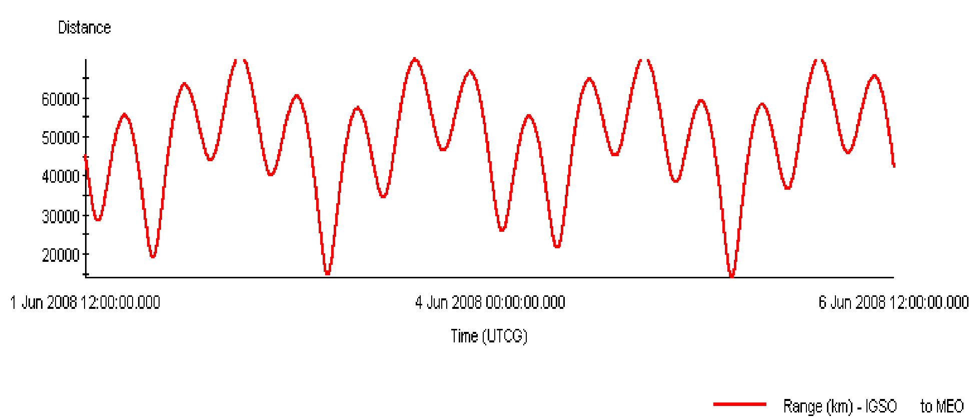
The simulation results suggest that the intersatellite link length between satellites at different orbit altitudes varies greatly, ranging from several hundred kilometers to tens of thousands of kilometers. In order to establish intersatellite links in such a 3-layer satellite network, we need to perform a detailed comparative analysis of the performance of links.



(a) Rules of the variation of intersatellite distance between GEO and IGSO



(b) Rules of the variation of intersatellite distance between GEO and MEO



(c) Rules of the variation of intersatellite distance between IGSO and MEO

Fig. 2: Rules of the variation of intersatellite distance within the 3-layer satellite networks

Table 1: Intersatellite link lengths of 3-layer satellite networks

	Link length (unit: km)	
Link types	dc (min)	dc (max)
GEO-IGSO	377.3	53957.058485
GEO-MEO	13670.1	69457.960023
IGSO-MEO	13946.4	69672.981513

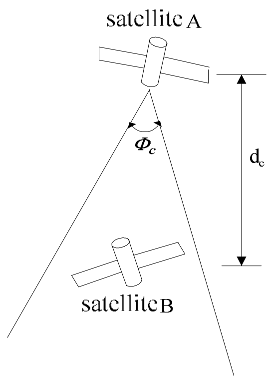


Fig. 3: Interlayer link model consisting of two satellites in different orbital altitudes

Performance calculation of intersatellite microwave links of the 3-layer satellite networks:

Basic built-up model of interlayer links: To realize data communication between the satellites constituting the 3-layer satellite networks, we need to establish several intersatellite links to build a topological structure. In the link structure between multiple satellites, the most elementary links are intersatellite links formed by two satellites of different orbit altitudes, as shown in Fig. 3 (Huang *et al*., 2012b).

In Fig. 3, satellite A and satellite B are located at different orbit altitudes. Two identical antennas with a diameter of D and a beam width of Φ_c are pointing at each other. The intersatellite distance between both satellites is d_c. The equivalent noise temperature of satellite B is T_e.

Performance calculation of interlayer links: In the Fig. 3, the satellite A transmitting power is P_t, antenna gain is G_t; for satellite B, the receiver antenna gain is G_r, the received signal power is P_r and carrier wavelength is λ; in the calculation, if only the free space loss, ignoring other link loss, the formula for calculating the intersatellite links can be obtained as follows (Kolawole, 2002):

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d_c}\right)^2 \quad (3)$$

where, the value G_t and G_r can be obtained by the following formula:

$$\begin{cases} G_t = \dfrac{4\pi}{\varphi_c^2} \\ G_r = \dfrac{4\pi}{\lambda^2} A_e \end{cases} \quad (4)$$

Φ_c indicates the beam width of transmitting antenna, which depends on the antenna diameter D and transmitting frequency; A_e indicates the antenna effective aperture area, which is the product of actual aperture area and antenna efficiency, formula is as follows:

$$\phi_C = \frac{\lambda}{D} \quad (5)$$

$$A_e = \frac{\pi}{4} D^2 \eta \quad (6)$$

By substituting (3) into (4), (5) and (6), obtaining:

$$P_r = \frac{\pi P_t D^4 \eta}{4\lambda^2 d_c^2} \quad (7)$$

Total noise power N of the receiver side is:

$$N = \kappa T_e B \quad (8)$$

where, k indicates the Boltzmann constant, whose value is 1.38×10^{-23} J/K. T_e indicates the equivalent noise temperature and B indicates the carrier bandwidth. Through formula (7) and (8), C/N can be obtained:

$$\frac{C}{N} = \frac{P_r}{N} = \frac{\pi P_t D^4 \eta}{4N\lambda^2 d_c^2} \quad (9)$$

Through the relationship between E_b/N_0 and C/N, obtaining:

$$\frac{E_b}{N_0} = \frac{C}{N} \cdot \frac{B}{r_b} = \frac{\pi P_t D^4 \eta}{4\kappa T_e \lambda^2 d_c^2 r_b} \quad (10)$$

where, r_b indicates the intersatellite information transmission rate.

ANALYSIS AND COMPARISON OF PERFORMANCE OF INTERSATELLITE MICROWAVE LINKS OF 3-LAYER SATELLITE NETWORKS IN S-BAND AND KA-BAND

Performance calculation of interlayer links preset conditions for performance analysis of microwave links: Let the design of intersatellite links using Binary

Table 2: GEO-IGSO link S-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	273.8	1.4×10^3	2.7×10^3	1.4×10^4
0.50 *m*	4.4×10^3	2.2×10^4	4.4×10^4	2.2×10^5
1.00 *m*	7.0×10^4	3.5×10^5	7.0×10^5	3.5×10^6

Table 3: GEO-MEO link S-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	165.3	826.3	1.7×10^3	8.3×10^3
0.50 *m*	2.6×10^3	1.3×10^4	2.6×10^4	1.3×10^5
1.00 *m*	4.2×10^4	2.1×10^5	4.2×10^5	2.1×10^6

Table 4: IGSO-MEO link S-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	164.2	821.2	1.6×10^3	8.2×10^3
0.50 *m*	2.6×10^3	1.3×10^4	2.6×10^4	1.3×10^5
1.00 *m*	4.2×10^4	2.1×10^5	4.2×10^5	2.1×10^6

Table 5: GEO-IGSO link Ka-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	4.3×10^4	2.1×10^5	4.3×10^5	2.1×10^6
0.50 *m*	6.8×10^5	3.4×10^6	6.8×10^6	3.4×10^7
1.00 *m*	1.1×10^7	5.5×10^7	1.1×10^8	5.5×10^8

Table 6: GEO-MEO link Ka-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	2.6×10^4	1.3×10^5	2.6×10^5	1.3×10^6
0.50 *m*	4.1×10^5	2.1×10^6	4.1×10^6	2.1×10^7
1.00 *m*	6.6×10^6	3.3×10^7	6.6×10^7	3.3×10^8

Table 7: IGSO-MEO link Ka-band parameter variations

D	r_b (b/s) P 1 *W*	5 *W*	10 *W*	50 *W*
0.25 *m*	2.6×10^4	1.3×10^5	2.6×10^5	1.3×10^6
0.50 *m*	4.1×10^5	2.1×10^6	4.1×10^6	2.1×10^7
1.00 *m*	6.6×10^6	3.3×10^7	6.6×10^7	3.3×10^8

Phase Shift Keying (BPSK) as modulation mode, if the Required Bit Error Rate (BER) is not more than 10^{-5}, taking the 2 dB of implementation margin into account, thus obtained E_b/N_0 is 11.6 dB. The equivalent noise temperature (i.e., T_e) of satellite receiver is 1000 K and receiving antenna efficiency η is 65% (Kolawole, 2002; Roddy, 2001). Without taking intersatellite antenna pointing error into account, conduct calculation and analysis for the S-band and Ka-band performance of link GEO-IGSO, link GEO-MEO and link IGSO-MEO through formula (10), obtaining the relationship among satellite transmitting power, antenna diameter and intersatellite information transmission rate.

S-band links performance analysis: When S-band and frequency 2.4 Ghz is used for intersatellite link carrier, put the given parameters into formula (10), the GEO-IGSO, GEO-MEO and IGSO-MEO link performance calculation results are shown in Table 2, 3 and 4 (Huang *et al*., 2010b).

Analyzed the results of Table 2, 3 and 4, which show that in S-band 2.4 GHz carrier, under the preset intersatellite transmission system, link parameters, transmission loss and without regard to the error of the intersatellite pointing accuracy, the intersatellite links can meet a certain high data rate requirements. When required transmission rate should reach 2 Mbps above and the antenna with a diameter of 1 m is used, the required transmitting power for GEO, IGSO and MEO satellite shall be about 50 W. Therefore, when using S-band carrier, relatively larger antenna and transmit power are required, in order to meet the requirements of intersatellite links date transmission rate in the 3-layer satellite networks, which makes higher requirements for the performance of the satellite.

Ka-band links performance analysis: Currently with the continuous development of the intersatellite communication, the requirements for information transmission rate are getting higher and higher. So the building of intersatellite links at Ka-band is considered, which has very little free space loss and the requirements for the antenna and transmitting power are also low. Under the preset intersatellite transmission system, link parameters, transmission loss and without regard to the error of the intersatellite pointing accuracy, with Ka-band 30 GHz carrier, to conduct re-calculation and analysis for link GEO-IGSO, GEO-MEO and IGSO-MEO and the results are as shown in Table 5, 6 and 7 (Huang *et al*., 2012).

Results of Table 5, 6 and 7 shows that when with the maximum distance among satellites link in GEO-IGSO, GEO-MEO and IGSO-MEO, with only 1 W of 1 m antenna, the 2 Mbps above intersatellite transmission data rate can be met. It can reduce the requirements for satellite antenna and transmitting power and can improve the intersatellite data transmission rate within the 3-layer satellite networks.

CONCLUSION

With the consideration of requirements on highly accurate time frequency of all kinds aerospace application systems in the future and on the basis of simulation of visual features and the variation range of the intersatellite links distance of 3-layer satellite networks, an aerospace time synchronization architecture based on layering is designed and the correspondent time synchronization links performance is analyzed. This layering time synchronization architecture adopts GEO satellite as its time synchronization source. GEO satellites realize intersatellite time synchronization with IGSO satellites and MEO satellites with the establishment of intersatellite links. Furthermore, an analysis is performed on the communication performance of GEO-IGSO, GEO-MEO and IGSO-MEO intersatellite microwave links in S-band and Ka-band without regard to the intersatellite pointing error. The results show that at the maximum intersatellite distance, if the S-band transmission rate is in excess of 2 Mbps, when the antenna is 1 m in diameter, the transmitting power needed is about 50 W. In the Ka-band, 1 m antennas only need 1 W transmitting power to provide an intersatellite data transmission rate higher than 2 Mbps. Therefore Ka-band is more favorable for improving the communication performance of the aerospace layering time synchronization architecture. Ultimately, the layering aerospace high-accuracy system time frequency standard is constructed. Those studies provide a important reference for the establishment of the aerospace layering time synchronization architecture and intersatellite microwave links. By taking advantage of this time frequency standard, highly accurate time service can be provided to various aerospace application systems.

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