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Design and Implementation of the Inter-Satellite Link Budget Software

[1]Huang Feijiang, [2,3]Lu Xiaochun, [1]Li Zhengda, [1]Zhang Junjun, [1]Deng Rong and [1]Liu Guangcan

[1]Department of Electronic Information and Electrical Engineering, Changsha University, Changsha, 410022, China
[2]National Time Service Center, Chinese Academy of Sciences, Xi'an, 710600, China
[3]Key Laboratory of Precision Navigation and Timing Technology, Chinese Academy of Sciences, Xi'an, 710600, China

Corresponding Author: Liu Guangcan, Department of Electronic Information and Electrical Engineering, Changsha University, Changsha, 410022, China

ABSTRACT
In order to make a budget analysis of the inter-satellite link performance quickly and accurately, this study proposes an inter-satellite link budget software design plan. Based on the methods to calculate the space coordinates of two satellites to determine their inter-satellite distance, the inter-satellite microwave link budget and laser link budget method by investigating the given satellite orbit parameters, it completes the designs of the inter-satellite distance calculation module, the microwave link calculation module and the laser link calculation module in the inter-satellite link budget software and realizes the human-computer interface of the inter-satellite link budget software via the GUIDE of MATLAB. With the given GPS satellite ephemeris parameters, it makes a budget of the inter-satellite link of GPS by using this software, analyzes the relationship among the transmission power, the information rate and the antenna aperture and proves that the calculation result is correct. Since the operation of this software is quite simple, the users can calculate the transmission power, the information rate and the antenna aperture of the receiving end of the inter-satellite microwave link and laser link by using this software; therefore, it can provide an important ground for the design of the inter-satellite link.

Key words: Satellite communication, inter-satellite link, link budget, MATLAB

INTRODUCTION
As the satellite communication system carries more and more jobs, the number of the satellites moving around the earth increases continuously and the space networking of the satellite communication system is also becoming increasingly complicated (Hua *et al.*, 2014; Liu and Wang, 2012; Ning *et al.*, 2013; Fan *et al.*, 2013). Under this circumstance, the construction of the inter-satellite link has become an important link in the networking, thus making the inter-satellite link budget become more and more important (Lin *et al.*, 2010; Han *et al.*, 2012; Li and Zhang, 2000). The parameters needed to be calculated in the inter-satellite link budget include: The transmission power of the sending end, the link information rate and the antenna aperture of the receiving end (Huang *et al.*, 2012). In making link budget, some sheets are created by using calculator or Excel. Although, the calculator has increased the efficiency of the manual calculation,

the non-professionals will still think it difficult because of the numerous calculation formulas and the tedious calculation steps. Although, the calculation by creating sheets with Excel has solved the problem of complicated operations of the calculator, these sheets fail to provide a friendly human-computer interface; besides, there can't be too many related parameters, otherwise this software will become cluttered, making it difficult to distinguish the necessary parameters. In addition, Excel will put the calculation formulas, all the formulas and the calculation results in just one page, making it inconvenient to upgrade and maintain and easy to cause mis-operations (Zhu and Hao, 2013; Meng, 2007). Therefore, it is absolutely necessary to design the inter-satellite link budget software with friendly interface, simple operations and convenient maintenance and upgrade.

MATERIALS AND METHODS

Methods to calculate the inter-satellite distance: After building the satellite orbit plane coordinate system and WGS-84 coordinate system, to calculate the satellite position is to calculate its coordinate (x, y, z) in the orbit plane coordinate system according to the given satellite orbit parameters (undisturbed parameters and disturbed parameters) and refer to the specific calculation process in the references (Xie, 2012). After that, calculate the coordinate (X, Y, Z) of the satellite in WGS-84 coordinate system according to the coordinate transformation Eq. 1:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x\cos\Omega - y\sin\Omega \\ x\sin\Omega + y\cos\Omega\cos i \\ y\sin i \end{bmatrix} \tag{1}$$

Assuming that the computed coordinate of satellite S1 and the coordinate of satellite S2 are (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2), it is easy to compute the inter-satellite distance d according to Eq. 2:

$$d = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2 + (Z_2 - Z_1)^2} \tag{2}$$

According to the above method to calculate the inter-satellite distance, it calculates the variations of its inter-satellite distance, as indicated in Fig. 1 by taking the two satellites PRN01 and PRN02 of GPS as example. It can be seen from Fig. 1 that the inter-satellite distance won't

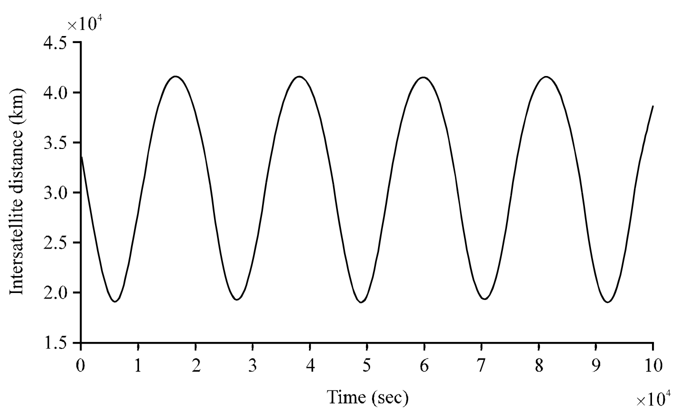

Fig. 1: Variations of the inter-satellite distance of MEO

remain unvaried; instead, it varies periodically within 18000-42000 km; therefore, it needs to find out the maximum distance between the two satellites when making a link budget. The relative position of any two satellites can be calculated by repeating this process.

Microwave link budget method: In order to meet the overall performance of the system in the inter-satellite link budget, it needs to analyze the bit energy-to-noise density ratio (Eb/N0) which can be calculated by comparing the Bit Error Rate (BER) since it has something to do with BER. In the digital signal transmission (Eb/N0) depends on the carrier-to-noise ratio of the receiver; therefore, after computing the carrier power C received by the satellite receiver and the total noise power N of the receiver, the relationship between Eb/N0 and the link parameters through the relationship between C/N and Eb/N0 and the inter-satellite communication performance requirements can be satisfied by optimizing the parameters in the link analysis.

Assuming that the transmission power of the satellite is P_t, the antenna gain is G_t, the receiving antenna gain is G_r, the receiving signal power is P_r, the carrier wave length is ë and the equivalent noise temperature is T_e, the calculation formula of the inter-satellite link performance can be obtained (Xi *et al.*, 2006; Kolawole, 2002) which is indicated as follows by only taking the free-space loss rather than other link losses into consideration:

$$\frac{E_b}{N_0} = \frac{C}{N} \cdot \frac{B}{r_b} = \frac{\pi P_t D^4 \eta}{4 \kappa T_e \lambda^2 d_c^2 r_b} \tag{3}$$

In Eq. 3, r_b is the inter-satellite information transmission rate; k is the Boltzmann constant which is 1.38×10^{-23} J K^{-1}; η is the antenna efficiency and E_b/N_0 is the bit energy-to-noise density ratio which has something to do with Bit Error Rate (BER) and its required value can be obtained by comparing the requirement of BER.

Laser link budget method: Assuming that the sending and receiving gains of the satellite antenna in the inter-satellite laser communication are G_T and G_R, respectively and the optical transmitter power is P_T, the optical power P_R received by the receiving antenna can be calculated as (Jiang and Fan, 2005):

$$P_R = P_T + G_T + G_R - [L_P + \Sigma_L + S_F] \tag{4}$$

L_P in Eq. 4 is the path loss and its value is:

$$L_p = [82 + 20\log\frac{d_c}{\lambda}]\text{dB} \tag{5}$$

where, d_c in Eq. 5 is the inter-satellite distance with kilometer as its unit and is the laser wave length with meter as its unit.

Σ_L includes other losses apart from the path loss and these losses have no unvaried data to be adopted so that it can be 7 dB and S_F can be 5 dB according to the international practice (Jiang and Fan, 2005). When the antenna in Eq. 4 is lenticular or reflecting telescope and G_T and G_R can be calculated according to the following equation:

$$G_i = 10\log(\frac{\pi D_i}{\lambda_i}) \tag{6}$$

D_i in Eq. 6 is the antenna aperture with meter as its unit.

When the inter-satellite laser link adopts PIN photoelectric detector to realize heterodyne synchronous detection, S/N can be (Jiang and Fan, 2005):

$$\frac{S}{N} = \frac{\xi P_R}{\Delta f h v} \tag{7}$$

In Eq. 7, ξ is the quantum efficiency which is defined as the electron number which can be generated by the photon of every input PIN; ν is the frequency of the incident light with Hz as its unit; $h = 6.626\times10^{-34}$ J sec and is Planck constant and Δf is the unilateral broadband and the baseband signal code rate $r_b = 2\Delta f$. The output current of PIN detector is firstly sent to the relevant demodulator for quadratic demodulation and the baseband signal current sent to the arbiter is I. After setting decision current, the Bit Error Rate (BER) P_e after PSK signal demodulation can be expressed as:

$$\begin{cases} P_e = \frac{1}{2}\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right) = \frac{1}{2}\mathrm{erfc}(Q') \\ Q' = \frac{Q}{\sqrt{2}} \end{cases} \tag{8}$$

When $P_e = 10^{-9}$, $Q' = 6$ and $\xi = 1$ and integrating Eq. 7, the necessary P_e is:

$$P_R = \left(\frac{S}{N}\right)\cdot hv\cdot \Delta f/\eta = 18hv\cdot r_b \tag{9}$$

Therefore, the inter-satellite data transmission rate of the corresponding laser link can be obtained as:

$$r_b = \frac{P_R}{18hv} \tag{10}$$

Overall design of the inter-satellite link budget software: By making requirements analysis of the inter-satellite link budget software, the software is divided into the interface part and the calculation function module and the overall design diagram is indicated as Fig. 2.

The inter-satellite link budget software calculates according to the relevant parameters input by the users; therefore, a friendly software interface is needed for the users to input the relevant parameters. The inter-satellite link is divided into the microwave link and the laser link and there are some differences in the parameters of these two links. The software interface part can be divided into the microwave link interface and the laser link interface and the parameters involved in the inter-satellite link budget include the ephemeris parameters to determine the satellite position, the antenna feeder parameter and the modulation demodulation system. Therefore, these parameters should also be included in the interface part of these two link budgets. The inter-satellite link budget mainly needs to calculate the transmission power of the sending end, the link information rate and the antenna aperture of the receiving end; therefore, the functional module of this software is mainly to realize the mutual calculation of these three parameters. In the

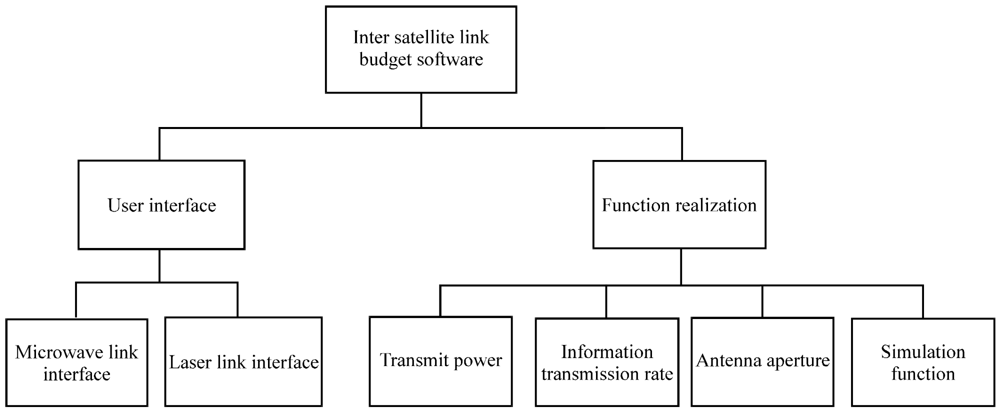

Fig. 2: Overall design diagram of the inter-satellite budget software

meanwhile, it adds the performance simulation function of the inter-satellite distance, the free-space loss, the antenna gain and the modulation demodulation system and the users can draw the necessary curve as required.

Interface design of the inter-satellite link budget software: Based on the GUI operating mode of MATLAB, the static text can be used to indicate the parameter name and the unit related to the parameter and the editable text can be used to receive such necessary parameters as the antenna and the modulation demodulation system in the calculation input by the users and to demonstrate the results. The satellite ephemeris chooses the sending and receiving satellites by uploading the file with a suffix of ".mat" with a control to open the files and a pull-down menu. It calculates the transmission power, the information rate and the antenna aperture by using the callback function of the button control and the calculation type of the pull-down menu. In order to realize the simulation of the parameters involved in the link, a menu named as "drawing simulation" is designed in the menu bar and connect the relevant sub-menus. The completed microwave link budget interface is indicated as Fig. 3.

Design of the calculation module: The calculation module is mainly divided into: The satellite position calculation module, the inter-satellite distance calculation module, the free-space-loss calculation module, the antenna gain calculation module and the button callback function calculation module. The callback function is also divided into the laser link calculation and the microwave link calculation. The inter-satellite microwave link has similar calculation process to the inter-satellite laser link. The microwave link has the commonly-seen L, S, C, X, Ku and Ka frequency bands while the laser link can choose the 810 and 1550 nm wave length lasers. The satellite position calculation process can be indicated as Fig. 4 and the calculation process of the laser link in the callback function can be seen in Fig. 5.

Inter-satellite link budget software implementation: The software has set some initial parameters in the initial interface. When the users use this software, it needs to variation the parameters in the interface according to the practical requirements. After the users set the relevant parameters, click the "start" button; get the necessary inter-satellite link calculation result and draw the orbit form and position of the satellite with its specific operating procedure as indicated in Fig. 6.

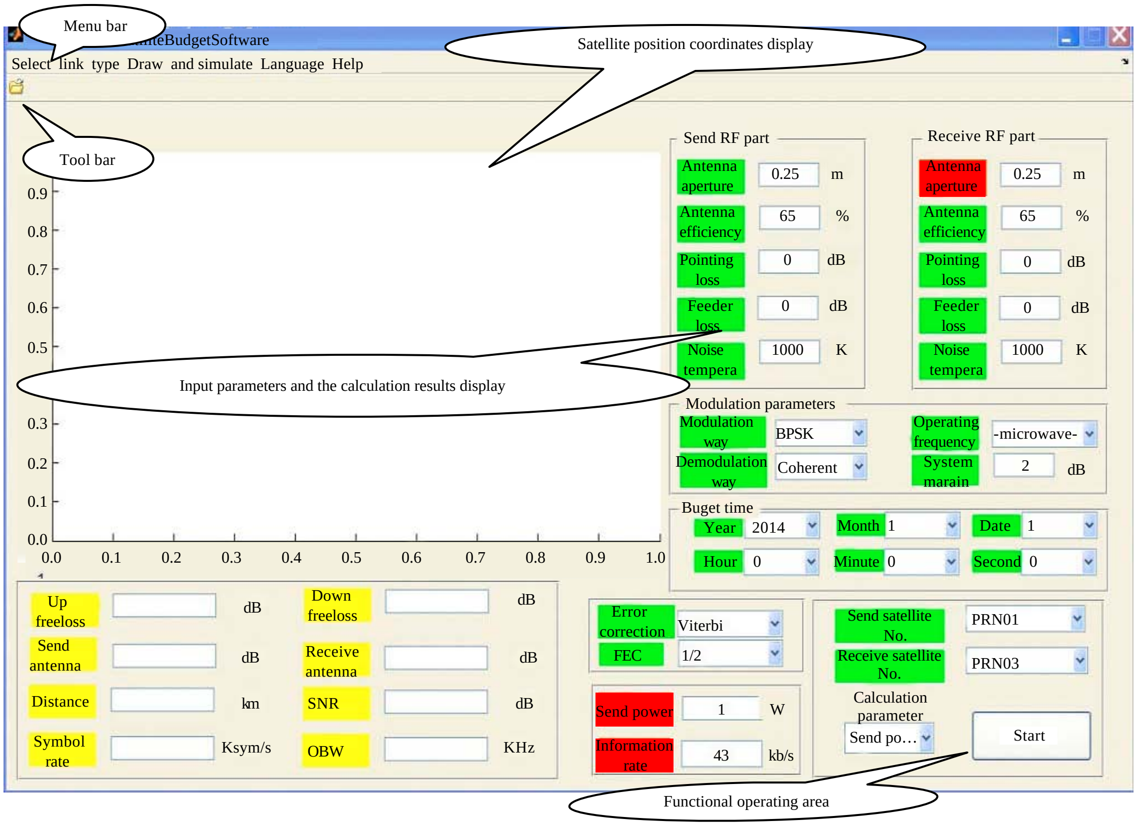

Fig. 3: Microwave link budget interface design plan

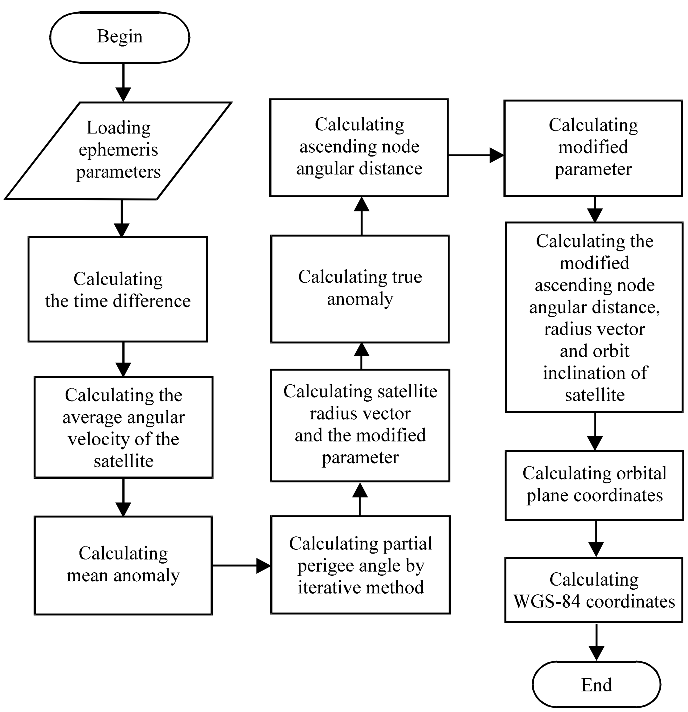

Fig. 4: Calculation flowchart of the satellite position

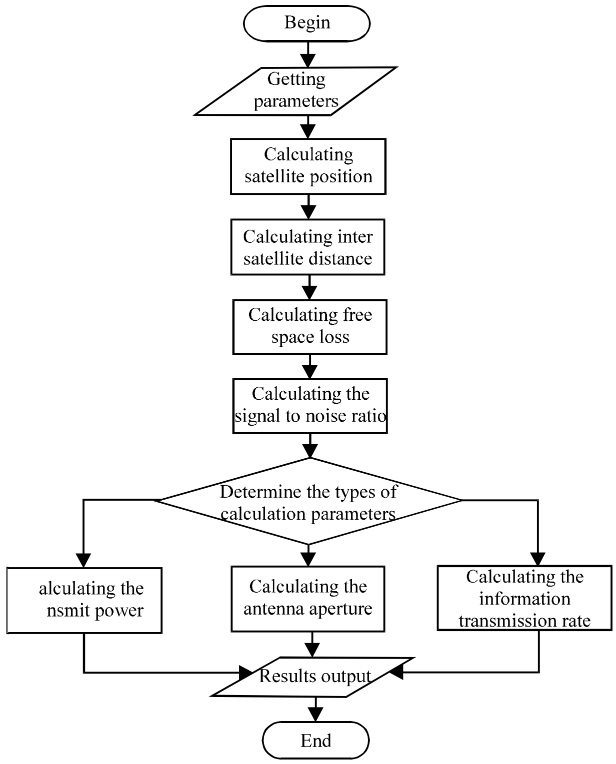

Fig. 5: Calculation flowchart of the callback function laser link

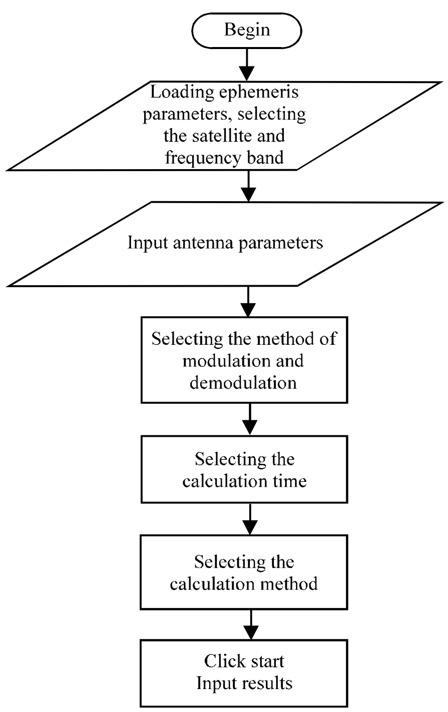

Fig. 6: Work flowchart of the inter-satellite link budget software implementation

RESULTS AND DISCUSSION

Analysis of the microwave link budget results: Assuming that the bit error rate P_e of the inter-satellite link is required to be no bigger than 10^{-6}, the calculated signal-to-noise ratio is 11.298 dB by adopting BPSK modulation. The signal-to-noise ratio is 13.298 dB without considering the feeder loss and the pointing loss of the antenna but 2 dB margin. Assuming that the inter-satellite distance of two MEOs is 41263.405 km, calculate its information rate by taking 30 GHz in Ka frequency band in the microwave link. Assuming that the antenna efficiency η is 65%; both the aperture D of the sending antenna and the receiving antenna is 0.25 m and the noise temperature T of the receiving antenna end is 1000 K (Roddy, 2001), the calculated information rate is 6.382×10^3 kb sec^{-1}, as indicated in Fig. 7 when the transmission power is 0.1 W.

When choosing the type of the calculation parameter is the transmission power or the information rate, calculate the necessary parameters and get a set of data after numerous calculations with the same method by taking 30 GHz in Ka frequency band as example.

In Table 1, it can be seen horizontally that the information rate r_b of the inter-satellite microwave link is proportional to the transmission power P_t while it can be seen vertically that with the same aperture in the receiving and sending antennas in the inter-satellite microwave link, the information rate r_b is proportional to the fourth power of the antenna aperture D. Therefore, increase the transmission rate or the antenna aperture in order to improve the information rate of the inter-satellite microwave link and the effect is more obvious by increasing the antenna aperture.

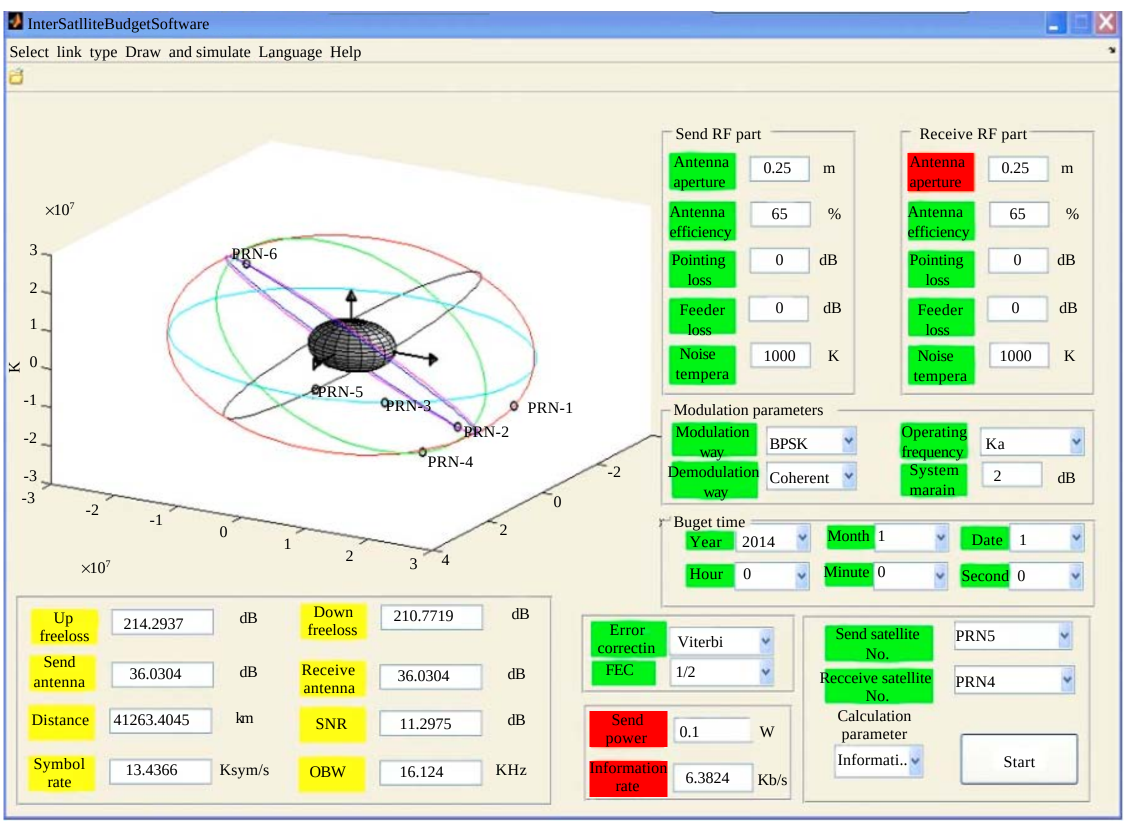

Fig. 7: Result of the inter-satellite microwave link information rate calculation

Table 1: Results of Ka frequency band microwave link calculation

	r_b (b sec^{-1}) / P_t (W)				
D (m)	0.1	1	5	10	50
0.25	6.382×10^3	6.382×10^4	3.191×10^5	6.382×10^5	3.191×10^6
0.50	1.021×10^5	1.021×10^6	5.106×10^6	1.021×10^7	5.106×10^7
1.00	1.634×10^6	1.634×10^7	8.169×10^7	1.634×10^8	8.169×10^8

Table 2: Results of S frequency bank microwave link calculation

	r_b (b sec^{-1}) / P_t (W)				
D (m)	0.1	1	5	10	50
0.25	4.085×10^1	4.085×10^2	2.042×10^3	4.085×10^3	2.042×10^4
0.50	6.536×10^2	6.536×10^3	3.268×10^4	6.536×10^4	3.268×10^5
1.00	1.046×10^4	1.046×10^5	5.228×10^5	1.634×10^6	5.228×10^6

Table 3: Result of 810 nm laser link calculation

	r_b (b sec^{-1}) / P_t (W)				
D (m)	0.1	1	5	10	50
0.25	2.650×10^8	2.650×10^9	1.325×10^{10}	2.650×10^{10}	1.325×10^{11}
0.50	4.241×10^9	4.241×10^{10}	2.120×10^{11}	4.241×10^{11}	2.120×10^{12}
1.00	6.785×10^{10}	6.785×10^{11}	3.393×10^{12}	6.785×10^{12}	3.393×10^{13}

With 2.4 GHz of S frequency band as example, calculate a set of data by using the same method, as indicated in Table 2.

Compared with Table 2 and 1, it can be seen that with the other equivalent parameters, S frequency band microwave link is 2 orders of magnitude lower than Ka frequency band microwave link; therefore, in order to obtain higher information rate, the operating frequency band of the link can be improved.

Analysis of the laser link budget results: The inter-satellite laser link budget takes the commonly-used 810 and 1550 nm wave length laser as example with the inter-satellite distance as 41263.405 km (Zhao *et al*., 2011). The budget result of the information transmission rate of the 810 nm wave length laser link is indicated as Fig. 8.

Calculate the 810 and 1550 nm wave length laser, respectively with the same method and the results are indicated as Table 3 and 4.

It can be seen easily from Table 3 and 4 that the laser link can provide high information rate; with the other equivalent inter-satellite parameters, the information rate is proportional to the transmission power in the inter-satellite laser link; with the same receiving and sending antenna aperture, the information rate is proportional to the fourth power of the antenna aperture and the higher the laser frequency, the higher the information rate. The conclusion in the microwave link

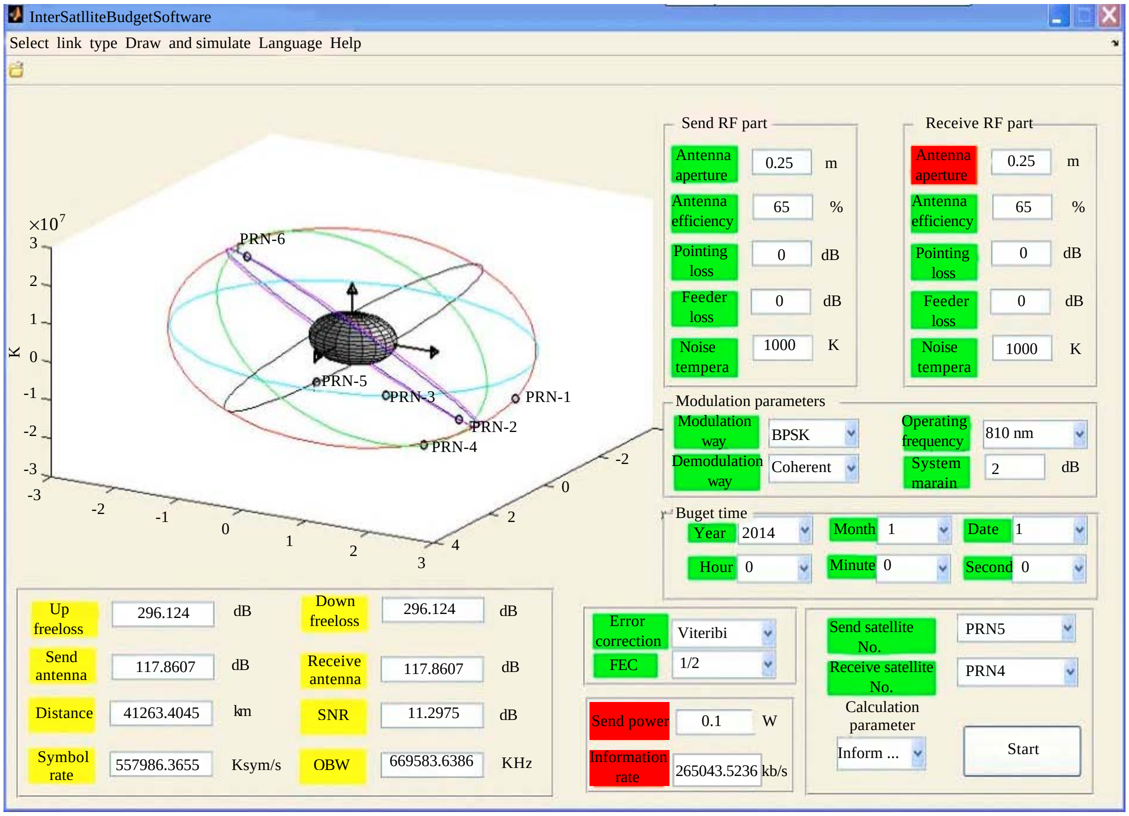

Fig. 8: Calculation results of the information rate of the inter-satellite laser link

Table 4: Result of 1550 nm laser link calculation

	r_b (b sec^{-1})				
	P_t (W)				
D (m)	0.1	1	5	10	50
0.25	1.385×10^{8}	1.385×10^{9}	6.925×10^{9}	1.385×10^{10}	6.925×10^{10}
0.50	2.216×10^{9}	2.216×10^{10}	1.108×10^{11}	2.216×10^{10}	1.108×10^{12}
1.00	3.546×10^{10}	3.546×10^{11}	1.773×10^{12}	3.546×10^{12}	1.773×10^{13}

is also applicable in the laser link. Besides, it can be seen from the comparison of the budget results of the microwave link and the laser link, the laser link is superior to the microwave link in the performance.

In conclusion, inter-satellite link budget results can be quickly and accurately obtained by the budget software.

CONCLUSION

According to the requirements of the inter-satellite link budget, this paper studies the inter-satellite distance calculation method, the inter-satellite microwave link budget method and the inter-satellite laser link budget method based on the satellite ephemeris, proposes a design plan of the inter-satellite link budget software and successfully develops the inter-satellite link budget software with friendly interface and simple operations in the GUI operating mode of MATLAB R2010 b development platform. This software calculates the transmission power, the information rate and the antenna aperture of the receiving end of the inter-satellite microwave link and laser link and simulates the various parameters involved in this budget. On this basis, it makes budget comparison of the S frequency band and Ka frequency band of the inter-satellite microwave link and the 850 and 1550 mm wave length of the inter-satellite laser link and the calculation results are quick and accurate. The budget results of this software can be an important reference for the design of the inter-satellite link.

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