

Chapter 2

The Key Questions Discussing of the Inter-Satellite Link (ISL) Signal Design Based on Earth-Moon System

Jianjun Fan, Yang Yang and Min Li

Abstract There are four kinds of inter-satellite link (ISL) based on Earth-Moon Lagrange navigation system. The much larger difference in transfer distance leads to large signal level dynamic range. Therefore signal design has much difficulty. In order to simplify the complexity of satellite payload, an integrative ISL signal scheme based on CDMA technique is proposed. The question of signal frequency selection and near-far effect have been analyzed in this article. The scheme's feasibility is justified by theoretical modeling and simulation calculation in the end.

Keywords Inter-satellite link · Near-far effect · Frequency selection

2.1 Introduction

The Earth-Moon Lagrange navigation system which arranges a plurality of space navigation station at Lagrange libration points networks construction with near earth satellite navigation to meet navigation and positioning requirements such as autonomous operation of near earth satellite navigation and deep space exploration. There are four kinds of inter-satellite link which is between Lagrange navigation satellites, between navigation satellites near the earth, between Lagrange navigation satellites and navigation satellites near the earth, and between Lagrange navigation satellite and spacecraft users. Links are at the distance of 70,000–400,000 km, dynamic range for received signal level is large, and there are higher accuracy requirement and a large quantity of information transmission. The signal design is difficult, particularly to avoid in large dynamic signal condition signal interference problem [1–3]. In this paper, 4 links are designed that is based on the basic

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requirements and characteristics of the Lagrange navigation system. The signal designed is fully and rationally utilizing spectrum with the space tracking and navigation of spacecraft users sharing the same channel, namely the system using the orbit determination and time synchronization link also providing radio ranging service for all customer spacecraft, which greatly simplifies the load on the satellite design complexity but increases of signal design difficulty, including signal frequency selection and modulation mode selection, coding scheme, especially considering the effect of signal near-far effect for longer transmission distance. This paper will focus on above problems with analysis and discussion.

2.2 Analysis of Inter Satellite Link Characteristics

On the basis of the Earth-Moon Lagrange navigation system mainly consists of 3–5 navigation satellites (located in L1, L2, L3, L4, L5 navigation satellite) and near earth navigation constellation (24 satellite). Lagrange navigation satellite can transmit navigation signal, the construction of inter satellite link between each other, distance observation and communication, and inter satellite link observation and communication with near navigation constellation composed of observation and communication system link, orbit determination and time synchronization processing system, and provides the Earth Moon space navigation application service. Between the Lagrange navigation satellite and near earth navigation satellite each constitute a relatively independent navigation system, through the construction of measurement and communication link between the Lagrange navigation satellites and near earth navigation satellite, can run autonomously to solve the near earth satellite navigation system is very good when the satellite constellation rotation problem. Signal integration design of 4 link, convenient device configuration is simple and uniform, and can avoid because of the different terminal to realize the kinds of system error and random error, is a basic principle of this inter satellite link signal design follow.

The inter-satellite link signal of the Earth-Moon Lagrange navigation system has the following characteristics: (1) large signal dynamic range. Four kinds of links are at the distance of 70,000–400,000 km, and the received signal level dynamic range is more than 8 dB. (2) The communication rate and measuring accuracy is limited. Because the satellite resources is limited, it is difficult to use a larger power to realize high speed data transmission. At the same time, long distance communication also has large space transmission loss, so generally ranging accuracy and data transmission rates are not high. The Lagrange system operation and navigation service requirements on ranging precision is about 0.3–3 ns and data transmission rate is not less than 500 bps, and even up to 5 kbps. System for spacecraft is not less than 25 bps to provide the transmission rate of the navigation message. (3) High

transmission delay. Transmission distance of 400,000 km has the transmission delay 1.3 s. Therefore, for deep space communications and navigation, real-time operation, control and communication is not possible.

According to the Consultative Committee for Space Data Systems (CCSDS) radio frequency and modulation proposal, there is no high bit rate transmission data transmission and ranging signals at the same time advice. The following will be integrated into communication and measurement requirements, equipment implementation ability and the future development trend of technology, planning the design of inter satellite link signal.

2.3 Design of Inter Satellite Link Signal

2.3.1 Frequency Selection

Frequency selection involves the following several problems: (1) frequency band selection. It is not only to meet the allocation rule of International Telecommunication Union (ITU), but also to consider the service demand for the comprehensive implementation of the ability, the influence of spatial transmission error and technology; (2) the two-way communication and measuring system working mode selection. The full duplex or half duplex communication mode decides the number of frequencies or band; (3) the multi access method selection for multi user signal. Selecting communication mainstream TDMA, FDMA or navigation field mainstream CDMA mode decides signal number in the single channel.

(1) Frequency band selection

Signal frequency band selection is mainly based on available carrier frequency ITU distribution. Frequency selection also comprehensively considers of several aspects such as the service demand, propagation effects and technology needs.

According to the radio regulations, VHF, UHF, L, S, Ka band and above Ka band can be used for the inter satellite link communication. In the navigation system, satellite ground links using L, S band, from the system electromagnetic compatibility perspective, inter satellite link is mainly selected from VHF, UHF and Ka bands.

In fact, the performance of millimeter wave active device determines the whole millimeter wave system performance to a great extent, but also limits the choice of working frequency band. Foreign technology is more advanced. The antenna, transmitter and receiver can be integrated in a MMIC chip which has the advantages of small volume, light weight, good consistency. At present the foreign has more than 100 GHz reports. According to the current level of millimeter wave active device which can realize the transceiver module under 35 GHz. For the current equipment implementation capacity, using the 32.3 GHz 33 GHz band is more suitable.

(2) Work mode selection

TDD and FDD belong to two different duplex mode. TDD stands for time division duplex, and belongs to half duplex. That is to say on the up and down link in the same frequency band according to the allocation of time for the cross. FDD represents a full duplex that the up and down link are in different frequency band at the same time. The two types of their respective advantages and disadvantages is that, TDD for uplink and downlink in the same frequency band, so it can better use of spectrum resources, easy to layout; and FDD for uplink and downlink at the same time, in different frequency bands act as one pleases, so the data transmission capacity is more. As mentioned earlier, data space transmission delay can reach to 1.3 s for the big link space transmission distance between satellites. Then considering the signal acquisition, tracking and stabilization time, half duplex TDD is low efficiency, and should not be selected. The choice of a two frequency band at the same time, two-way data transmission and signal measurement of continuous is the ideal way of working.

(3) The multiple access mode selection

The signal must be designed to avoid interference between different satellite signals, so as to ensure that the receiver can distinguish between different signal. FDMA, TDMA and CDMA is the most commonly used several multiple access modes in currently the radio communication and navigation system.

Using orthogonal CDMA code sequence for implementing different satellite access, different satellite signal overlap in the frequency spectrum and time domain. The current navigation field and recent development of 3G system and CDMA2000 just use code division multiple access.

The separation of different satellite signal spectrum access is realized by FDMA, and different signal overlap in time domain and code domain. Frequency division multiple access allocates a single channel to individual users, such as the GLONASS of each satellite using a band only. In a large number of users, the system cost is higher than that of TDMA system. The main reason is the need for RF front end terminal unit with ultra wide band, also need to configure the expensive bandpass filter.

TDMA is to launch a satellite signal at the different time to avoid interference in the system. A major feature of TDMA is the data transmission or location is not continuous, and the demand for bandwidth is smaller. For the 400,000 km of transmission distance, inter satellite link signal space transmission time reached about 1.3 s, so the signal chain building time is too long and the signal acquisition and tracking is very difficult. Therefore it does not recommend the application of the multiple access mode.

Based on the above analysis, CDMA is proposed mode of multiple access.

According to the choice of frequency selection, working mode and multiple access mode, the 2 bands in the 32.3 GHz 33 GHz frequency range is chosen. Considering the transmitter receiver isolation, we selected the center frequency of 43.50103 GHz/43.56241 GHz, bandwidth of send and receive pairing, respectively

44 MHz. The bit rate of 20.46 Mcps is chosen. The code length is tentatively scheduled for 10,230 bit, and it can be extended according to the equipment to realize the ability.

2.3.2 Modulation Mode Selection

Any communication system or a navigation system in the selection of modulation mode, power efficiency and bandwidth efficiency are the two most important factors. The frequency band and the power performance have the good performance, and can simultaneously carry out the modulation data transmission and ranging from QPSK/OQPSK, MSK/GMSK. MSK has a characteristics of constant envelope and small power out of band. But zero bandwidth of MSK is 1.5 times of that of BPSK, and the realization of the receiver in the satellite has difficulties. In fact, for the effective mode power, CCSDS first proposed a QPSK modulation. QPSK has good error performance, and main lobe of signal modulation spectral is narrow. Because of the existence of the envelope fluctuation problem, QPSK is mainly applied to linear channel. Through reducing the envelope fluctuations and increasing RF power amplifier, frequency spectrum after this amplifier can be limited to the allowed range. QPSK envelope fluctuation is mainly due to symbol from two orthogonal branch with common starting time, and jumping $\pm 180^\circ$ in the phase symbol at conversion time. OQPSK solves these problems. OQPSK is deformation of QPSK through the shift of half a symbol, which makes the phase mutation maximum $\pm 90^\circ$, and reduce the signal envelope fluctuation. But the BER performance and bandwidth efficiency are same with QPSK. In fact, UQPSK is another kinds of deformation for QPSK with I/Q channel power regulation. UQPSK error performance and bandwidth efficiency are same with QPSK. It helps to improve the signal design flexibility, and balance the anti-interference ability of I/Q channels. The demodulation processing is simple, but the processing complexity is slightly higher than QPSK.

A comprehensive comparison of the spectral efficiency, error rate performance, the ranging performance and implementation complexity and so on many factors, OQPSK and UQPSK modulation (U-OQPSK) are suggestion choice as the inter satellite link system modulation, which can better balance the threshold difference for the ranging signal and digital signal, wherein the I branch is for ISL ranging, end users ranging and the information demodulation, Q branch is for inter satellite communication link.

2.3.3 Coding Mode Selection

The traditional coding methods, such as convolutional codes, linear block codes with short code length, RS and convolutional concatenated code, the coding gain is low. High gain channel coding scheme is used as far as possible, such as LDPC

Table 2.1 Scheme of inter satellite link signal for Lagrange navigation system

| Parameters | Content |
|---------------------|--|
| Center frequency | 43.50103 GHz/43.56241 GHz (Transceiver pairs) |
| Work width | 50 MHz |
| Modulation | UQPSK |
| The multiple access | CDMA |
| Code rate | 20.46 Mcps |
| Code length | 10,230 |
| I channel data rate | 25 bps |
| Q channel data rate | 500 bps |
| I channel code mode | Convolutional code |
| Q channel code mode | ½ LDPC |

code [4]. LDPC codes are block codes, the packet length is strictly limited by information timeliness requirements and inter satellite link payload hardware resource constraints. In the condition of aging demand is not high, the length may be 1000 or 2000. Packet length should not be too long, so the I channel is chosen as 1024. In accordance with the coding gain and spreading gain, 1/2 LDPC code is selected as the Q channel coding scheme. I channel information rate is low, so simple convolutional code is used.

In summary, link signal scheme between the satellites is seen in Table 2.1.

2.3.4 Link Budget

I channel signal is to be used as ranging and message broadcasting to meet the end user ranging and navigation requirements, the orbit determination and time synchronization ranging needs. Because the message rate were significantly lower than those of Q channel, the desired signal carrier to noise is lower than the threshold. So the carrier to noise ratio threshold of I channel mainly depends on the ranging threshold. Noncoherent discriminator ranging error calculation formula in accordance with BPSK modulation:

$$\sigma_{\tau} = T_c \sqrt{\frac{2d^2 B_n}{C/N_0} \left[2(1-d) + \frac{4d}{TC/N_0} \right]} \quad (2.1)$$

Table 2.2 Different ranging demands of the carrier to noise ratio threshold

| Ranging demands (ns) | Carrier to noise ratio threshold (dB-Hz) |
|----------------------|--|
| 0.3 | 34.9 |
| 1 | 28.2 |
| 10 | 18.8 |

Assuming that the receiver loop noise bandwidth of B_n is 0.1 Hz, the relevant interval of d is 1 chip, and the cumulative integral time T is 0.005 ms. According to the above formula, the ranging accuracy is to be achieved better than 0.3, 1 and 10 ns (1Sigma) of the carrier to noise ratio threshold as shown in Table 2.2.

Q channel signal is mainly used for data transmission. Considering the signal-to-noise ratio and the carrier to noise ratio between the coding gain:

$$\left[\frac{C}{N_0} \right] = \left[\frac{E_b}{N_0} \right] + 10 \log(R_b) + [L] - [G] \tag{2.2}$$

$\left[\frac{C}{N_0} \right]$ is carrier to noise ratio; $\left[\frac{E_b}{N_0} \right]$ is signal to noise ratio; R_b is data rate; $[L]$ is realization loss, the general is under 2 dB; $[G]$ is code gain.

Modulation mode is BPSK, the BER requirements is for 10^{-6} , and using coherent demodulation requires E_b/N_0 to 10.6 dB. Assuming the processing loss is 2 dB and Q channel coding gain is 9 dB, the carrier to noise ratio at receiving antenna aperture requirements is 30.6 dB-Hz.

In short, when the ranging precision is 0.3 ns, the signal carrier to noise ratio requirements is 34.9 dB-Hz. When the ranging accuracy requirements is 10 ns, the signal carrier to noise ratio requirements to Q channel is prevail of demodulation threshold, namely 30.6 dB-Hz.

Antenna gain has been achieved can reach 35 dBic, and emission EIRP of 40 dBW can be achieved. Therefore, the carrier to noise of the near earth navigation satellite received from Lagrange navigation satellite is such as shown in Table 2.3.

It can be seen from Table 2.3, the antenna gain under 35 dBic cannot satisfy the ranging accuracy 0.3 ns requirements, but the other needs can be satisfied. It is able to meet the Q channel data transmission and I channel 1 ns pseudorange measurements and 25 bps message broadcasting. When the antenna gain is increased above 3 dB, according to the link calculation, it can meet the requirements of 0.3 ns ranging accuracy obviously.

Table 2.3 The actual received carrier to noise ratio (a distance of 400,000 km)

| Parameters | Result |
|--|--------|
| Transmitting power (dBW) | 5 |
| A transmitting antenna gain (dBic) | 35 |
| Transmitting EIRP (dBW) | 40 |
| The path loss (dB) | 243.3 |
| Pointing, polarization loss (dB) | 2.0 |
| Receiving antenna gain (dBic) | 36 |
| The actual received carrier to noise ratio (dB-Hz) | 32.6 |

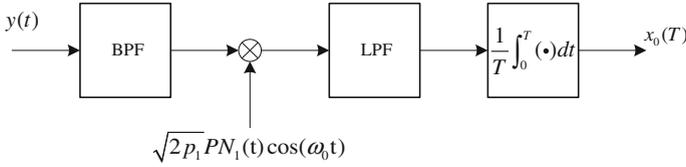


Fig. 2.1 The received CDMA signal model

2.4 Analysis of Near-Far Effect

Relative to other multiple access methods, CDMA is the most sensitive to the near far problem, and need to be carefully treated. In the near earth satellite navigation system of autonomous operation stage, the satellite can receive signals from Lagrange navigation satellite, also receive signals from other near navigation satellite. Signal level differences is above 8 dB. The weak signal receiving ability is needed to study. Assuming near navigation satellite with reference to the GPS constellation design, each near navigation satellite has also received 8 other near earth navigation satellite signal and the 2 Lagrange navigation satellite signal ability. Combined signal through the antenna and channel equipment after reference signal correlation demodulation, low pass filter, integral accumulation, the received model is shown in Fig. 2.1 [5].

The received signal plus interference and thermal noise model is shown below:

$$y(t) = \sum_{i=1}^N \sqrt{2p_i} d_i(t) PN_i(t) \cos(\omega_0 t) + \sqrt{2} n_c(t) \cos(\omega_0 t) + \sqrt{2} n_s(t) \sin(\omega_0 t)$$

In the formula, p_i is the signal power, $N = 10$, p_1 is Lagrange navigation satellite signal power, the other is near earth navigation satellite signal power; $d_i(t)$ is a baseband signal data; $PN_i(t)$ is spreading code applied in signal; The last two items is thermal noise which is modeled as Gauss random process.

Assumed that baseband equivalent filter function is $H_{BB}(f)$, and the bandwidth is B Hz. The output of the signal after the correlation demodulation with reference signal, low pass filter, integral accumulation is:

$$\begin{aligned} x_0(T) &= \sqrt{p_1} \int_{-\infty}^{\infty} H_{BB}(f) S_{d1}(f) df + \frac{1}{T} \sum_{i=2}^N \sqrt{p_i} \int_0^T d_i(t) PN_i(t) PN_1(t) dt + \frac{1}{T} \int_0^T n_c(t) PN_1(t) dt \\ &= s_0(T) + n_0(T) \end{aligned}$$

The noise part $n_0(T)$ is thermal noise plus other user interference signal, and its variance:

$$\text{Var}(n_0(T)) = \frac{1}{T} \int_{-\infty}^{\infty} S_{n_c}(f) S'_{PN_1}(f) df + \frac{1}{T} \sum_{i=2}^N \frac{P_i}{2} \int_{-\infty}^{\infty} S'_{PN_1}(f) S'_{PN_1}(f) df$$

where $R'_{PN}(\tau)$ is the unit power self-correlation function of $PN_i(t)$. Among them, $S_{n_c}(f)$ is a bilateral noise spectral density; $S'_{PN_i}(f)$ is signal unit power spectral density.

Considering the front-end bandpass filter restriction, it can get:

$$\text{Var}(n_0(T)) = \frac{N_0}{2T} \int_{-\infty}^{\infty} |H_{BB}(f)|^2 S'_{PN_1}(f) df + \frac{1}{T} \sum_{i=2}^N \frac{P_i}{2} \int_{-\infty}^{\infty} |H_{BB}(f)|^2 S'_{PN_1}(f) S'_{PN_1}(f) df$$

Equivalent noise spectrum density N'_0 is defined as below:

$$N'_0 = 2T \text{Var}(n_0(T))$$

Therefore, the equivalent noise spectrum density:

$$N'_0 = N_0 \int_{-\infty}^{\infty} |H_{BB}(f)|^2 S'_{PN_1}(f) df + \sum_{i=2}^N P_i \int_{-T}^T |H_{BB}(f)|^2 S'_{PN_1}(f) S'_{PN_1}(f) df$$

The above formula is simplified as:

$$N'_0 = v N_0 + \sum_{i=2}^N P_i I_0$$

Among them, $v = \int_{-\infty}^{\infty} |H_{BB}(f)|^2 S'_{PN_1}(f) df$,

$$I_0 = \int_{-T}^T |H_{BB}(f)|^2 S'_{PN_1}(f) S'_{PN_1}(f) df$$

v is usually very close to 1, I_0 is the spectral separation coefficient. In this case,

$$N'_0 = N_0 + \sum_{i=2}^N P_i I_0$$

According to the equivalent definition of carrier to noise ratio:

$$\frac{P_1}{N'_0} = \frac{P_1}{N_0 + \sum_{i=2}^N P_i I_0} = \frac{\frac{P_1}{N_0}}{1 + \sum_{i=2}^N \left(\frac{P_i I_0}{N_0}\right)} \quad (2.3)$$

The conventional BPSK (10) of the spectral separation coefficient is about -70.0 dB. Because the signal bandwidth and the rate are wide, on this signal design conditions spectral separation coefficient calculated is -74.0 dB.

According to the formula (2.3), in the spectral separation coefficient is -74.0 dB, the corresponding equivalent carrier to noise ratio is 32.6 dB-Hz, the receiving effect that other near navigation satellite signal to Lagrange navigation satellite signal can be ignored; in the spectral separation coefficient is -70.0 dB, the corresponding equivalent carrier to noise ratio is still about 32.6 dB-Hz. Thus, in this paper the assumption that the signal received quantity condition, smaller effect of strong signal of receiving weak signals, can be ignored.

Considering the theoretical limit, when the spectral separation coefficient of -74.0 dB, change the near earth satellite navigation signal number reached 1400, equivalent carrier to noise ratio reached 30.6 dB-Hz; and when the spectral separation coefficient of -70.0 dB, change the near earth satellite navigation signal number reached 570, carrier to noise ratio reached 30.6 dB-Hz equivalent. As can be seen, the influence of spectral separation coefficient of the user capacity is very big still, and illustrates the requirements of PN code correlation properties of the signal design is very necessary.

2.5 Conclusion

In this paper, the thorough research on the inter satellite link signal design is based on the Earth Moon system Lagrange navigation system. A design scheme based on CDMA multiple access is proposed from the aspects of frequency selection, modulation, the rate and coding method, and the ability of the future technology development trend considered communication and measurement requirements, equipment. The problem focuses on the work mode selection, multiple access near-far effect selection that CDMA system is sensitive to. Negligible influence on weak signal with receiving strong signal system is proved through theoretical modeling, simulation, so the signal design plan is feasible. Finally, the theoretical limit of the user capacity of the system is given, and that the spectral separation coefficient affect user capacity is pointed out, which is determined as a basic principle for pseudo code optimization.

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