

## Design and Simulation of a Novel Gold-Code-Modulated PN-DOR Beacon for VLBI Orbit Determination Postprint

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### Abstract

The Chinese VLBI Network (CVN) employs the delta differential one-way ranging ( $\Delta$ DOR) technique in lunar exploration missions, alternately observing the spacecraft and nearby compact radio sources to calibrate systematic errors, thereby obtaining high-precision angular position measurements of the spacecraft's orbit. Nevertheless, phase fluctuations in the receiving equipment caused by spectral differences between the spacecraft and radio source signals remain one of the significant error sources for  $\Delta$ DOR. By spread-spectrum modulating the DOR beacon with Gold codes, a pseudorandom noise differential one-way ranging (PN-DOR) beacon with spectral characteristics approximating those of radio sources can be generated, effectively reducing phase fluctuation errors. Referencing the VLBI beacon parameters of China's Chang'e-5 lunar exploration mission, PN-DOR beacon parameters were designed, PN-DOR beacons were generated, and simulation analysis of the PN-DOR beacon's encoding, modulation, extraction, demodulation, and decoding processes was completed. Additionally, since spectral aliasing may occur in subsequent lunar missions, the impact of spectral aliasing on PN-DOR was also investigated.

### Full Text

### Preamble

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# Design and Simulation of a New Gold-Code-Modulated PN-DOR Beacon for VLBI Orbit Determination

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## Abstract

The Chinese VLBI Network (CVN) employs delta differential one-way ranging ( $\Delta$ DOR) technology in lunar exploration missions. By alternately observing the spacecraft and nearby compact radio sources, this technique calibrates systematic errors to obtain high-precision angular position measurements of the spacecraft orbit. However, phase fluctuations in the receiving equipment caused by spectral differences between the spacecraft and radio source signals remain a significant error source for  $\Delta$ DOR. Spreading the DOR beacon with Gold codes to generate pseudorandom noise DOR (PN-DOR) beacons—which exhibit spectral characteristics similar to those of radio sources—can effectively reduce phase fluctuation errors. Referencing the VLBI beacon parameters from China’s Chang’e-5 lunar mission, this paper designs PN-DOR beacon parameters, generates PN-DOR beacons, and completes simulation analysis of the encoding, modulation, extraction, demodulation, and decoding processes. Additionally, since spectral aliasing may occur in future lunar missions, the impact of spectral aliasing on PN-DOR is investigated.

**Keywords:** VLBI; PN-DOR;  $\Delta$ DOR; Gold code

## 1. Introduction

Very Long Baseline Interferometry (VLBI) is a crucial interferometric measurement technique that combines multiple radio telescopes separated by hundreds or thousands of kilometers into a single synthetic aperture telescope, representing the highest-resolution astronomical observation technology currently available. It is widely applied in astrophysics, astrometry, geodesy, and deep space exploration. The Chinese VLBI Network consists of five VLBI stations (Tianma, Sheshan, Miyun, Kunming, and Nanshan) and the Shanghai VLBI Data Processing Center, which has participated in all of China’s lunar exploration missions and the first Mars exploration mission, playing an irreplaceable role during critical mission phases [1].

VLBI utilizes  $\Delta$ DOR measurement technology, which alternately observes the spacecraft and nearby compact radio sources to correct systematic errors from equipment and propagation media, yielding high-precision delay and delay rate measurements. China first conducted X-band  $\Delta$ DOR measurement experiments during the 2012 Chang'e-2 lunar mission, achieving post-processed orbit determination delay precision better than 0.5 ns [2]. Subsequent missions achieved 0.8 ns precision for Chang'e-3 and 0.7 ns for Chang'e-4 [3]. In 2020, China launched the Chang'e-5 lunar probe and the Tianwen-1 Mars probe, achieving average orbit determination delay precisions of 0.4 ns and 0.2 ns, respectively [4]. Currently, NASA's Deep Space Network achieves  $\Delta$ DOR measurement delay precision of 0.038 ns [5], indicating that a gap remains between Chinese and U.S.  $\Delta$ DOR measurement accuracy.

$\Delta$ DOR measurement precision is affected by numerous factors. Figure 1 [Figure 1: see original paper] shows the current delay precision achieved by NASA's Deep Space Network  $\Delta$ DOR measurements and the associated error source analysis [6]. Green items represent random errors, red items represent systematic errors, and gray items represent the root sum square (RSS) of all error terms. Systematic errors include radio source position errors, station position errors, and Earth rotation parameter errors, while random errors include delay errors caused by source thermal noise, clock instability, and receiving equipment phase fluctuations. Among all error sources, delay errors caused by receiving equipment phase fluctuations are the most significant, contributing to DOR delay measurement error as:

$$\epsilon_{\tau} = \frac{\epsilon_{\phi}}{360\Delta f}$$

where  $\epsilon_{\phi}$  is the phase fluctuation value and  $\Delta f$  is the maximum spacing of the DOR signal.

Phase fluctuations arise from the nonlinear phase-frequency response characteristics of receiving equipment. Figure 2 [Figure 2: see original paper] [6] illustrates the phase-frequency response of spacecraft DOR beacons and radio source signals under receiving equipment phase fluctuations. Radio source signals are broadband signals distributed across the entire recording channel, experiencing averaged equipment phase fluctuations within the channel bandwidth. In contrast, spacecraft DOR beacons are single-frequency signals affected by equipment phase fluctuations only at the DOR beacon frequency. The substantial spectral difference between the two prevents suppression of phase fluctuation effects through differential processing, thereby reducing  $\Delta$ DOR measurement delay precision.

To mitigate phase fluctuation effects, NASA's Jet Propulsion Laboratory (JPL) uses pseudorandom noise sequences to spread-spectrum modulate traditional DOR beacons, transforming them into wideband beacons known as PN-DOR beacons. PN-DOR beacons approximate radio source signal spectra, enabling

effective reduction of phase fluctuation effects through differential processing and thus decreasing phase fluctuation errors from receiving equipment. JPL has simulated X-band and Ka-band PN-DOR signals using MATLAB's Simulink tool, applying them to prototype designs for the Iris SN104 transponder on Mars orbiting microsatellites and universal space transponder transmitters [7, 8]. According to JPL's simulation analysis, PN-DOR beacons are expected to reduce measurement delay errors caused by phase fluctuation effects by 80%–90%, with total delay errors reducible by up to 40% [7].

Furthermore, by selecting longer code periods, PN-DOR beacons can achieve excellent delay ambiguity resolution capability, reducing requirements for prior orbit information. Traditional  $\Delta$ DOR relies on low-frequency DOR beacons for ambiguity resolution—for example, using 3.8 MHz DOR beacons in X-band. PN-DOR ambiguity resolution capability depends on code period, and through proper design of code period length, it can achieve far superior performance than traditional DOR. Consequently, only one set of PN-DOR beacons is sufficient for both ambiguity resolution and precise delay measurement, conserving frequency band resources [7]. By selecting PN code sequences with anti-interference performance, PN-DOR beacon anti-interference capability can be enhanced, enabling simultaneous reception of multiple PN-DOR beacons in the same frequency band and interference-free extraction of corresponding PN code sequences.

PN-DOR beacons evolve from traditional DOR beacons, and their data acquisition and processing methods are similar to those for traditional DOR beacons, allowing largely common hardware and software equipment. The primary difference is that PN-DOR signals require decoding of Gold code sequence information for ambiguity resolution.

This paper references the VLBI beacon parameters from China's Chang'e-5 lunar mission, selects Gold codes as spreading codes, and designs a set of PN-DOR beacon parameters. Referencing the VLBI data acquisition process, simulation analysis is conducted on PN-DOR beacon encoding, modulation, extraction, demodulation, and decoding. Additionally, since spectral aliasing may occur in future lunar missions, the impact of spectral aliasing on PN-DOR beacons is analyzed.

## 2. PN-DOR Beacon Parameter Design

This chapter introduces the spreading codes used for PN-DOR beacon generation and the parameter design principles and methods for shaping filters. Referencing the VLBI beacon parameters from China's Chang'e-5 lunar mission, a set of implementation parameters for PN-DOR beacons is designed.

### 2.1 Gold Code

To ensure PN-DOR beacon anti-interference performance, pseudorandom noise sequences are selected as spreading codes. The pseudorandom sequences should exhibit the following characteristics: (1) sharp autocorrelation properties; (2)

weak cross-correlation properties; and (3) the ability to generate a sufficiently large number of sequences. m-sequences and Gold code sequences are two widely used pseudorandom noise sequences that satisfy these properties.

An m-sequence is a maximum-length code sequence generated by multi-stage shift registers with linear feedback. An m-sequence generated by an n-stage shift register has a period of  $2^n - 1$  and exhibits good correlation properties. Gold code sequences are generated by performing bitwise modulo-2 addition of two m-sequence preferred pairs with identical length and clock rate. New Gold code sequences can be generated by changing the relative displacement between the two m-sequences. With  $2^n - 1$  possible relative displacements between the two m-sequences,  $2^n - 1$  sets of Gold code sequences can be obtained, plus the two basic m-sequences, yielding a total of  $2^n + 1$  sets of Gold code sequences [9]. As the number of stages n increases, the number of Gold code sequences far exceeds that of m-sequences at the same level. For example, when the shift register stage number n = 11, 126 sets of m-sequences can be generated, whereas 2,049 sets of Gold code sequences can be produced at the same level.

Gold code sequences retain the excellent correlation properties of m-sequences. Using stage number n = 11 as an example, Figure 3 [Figure 3: see original paper]a shows the autocorrelation properties of Gold code and m-sequences, while Figure 3 [Figure 3: see original paper]b shows the cross-correlation properties between any two Gold code sequences and two m-sequence preferred pairs. The normalized autocorrelation function maximum values for both m-sequences and Gold code sequences are 1, coinciding at the maximum point. Both exhibit sharp autocorrelation and weak cross-correlation, but Gold code sequences generally have smaller cross-correlation values than m-sequence preferred pairs, making it easier to separate target signals from mixed signals using Gold codes.

## 2.2 RRC Filter

Gold code sequences must undergo pulse shaping before being modulated onto a unified carrier for transmission; otherwise, sidelobes will be generated, causing signal energy dispersion and inter-symbol interference [10]. Since ideal rectangular pulses cannot be physically realized, a root raised cosine (RRC) filter is selected to shape the Gold code sequences, adjusting their spectral bandwidth to the target bandwidth before modulation and transmission.

RRC filter performance is determined by the roll-off factor and span coefficient. The roll-off factor primarily affects the transition band attenuation rate: a smaller roll-off factor results in faster attenuation and a narrower transition bandwidth. Figure 4 [Figure 4: see original paper] shows the amplitude-frequency response calculated for different roll-off factors with a span coefficient of 16. The span coefficient affects not only the transition bandwidth but also the sidelobe amplitude attenuation rate. Figure 5 [Figure 5: see original paper] presents the amplitude-frequency response for different span coefficients with a roll-off factor of 0.3. Combining Figures 4 and 5 reveals that smaller roll-off

factors and larger span coefficients produce flatter RRC filter passbands, narrower transition bandwidths, and faster sidelobe attenuation. Generally, smaller roll-off factors and larger span coefficients yield better RRC filter shaping performance but increase the complexity of practical logic system implementation, necessitating comprehensive consideration of multiple factors in parameter selection.

### 2.3 Gold Code and RRC Filter Parameter Design

In the Chang'e-5 lunar mission, the frequency channel bandwidth for recording radio source signals was 2 MHz; therefore, the PN-DOR beacon bandwidth  $W$  is designed to be 2 MHz. To achieve the flattest possible passband while ensuring all signal power remains within the observation frequency passband, the RRC filter roll-off factor  $\beta$  must satisfy  $\beta \leq 0.3$ . The bandwidth  $W$ , code rate  $R$ , and roll-off factor  $\beta$  satisfy the following relationship:

$$W = R(1 + \beta)$$

where  $W = 2$  MHz and  $\beta \leq 0.3$ . In simulation experiments,  $\beta = 0.25$  and  $R = 1.6$  Mc/s are adopted.

According to Consultative Committee for Space Data Systems (CCSDS) recommendations, to ensure PN-DOR beacons possess sufficient delay ambiguity resolution capability, the delay ambiguity  $P$  must be at least 1 ms, meaning the Gold code period must exceed 1 ms [6]. The linear shift register stage number  $n$ , delay ambiguity  $P$ , and code rate  $R$  satisfy:

$$n = \log_2(P \cdot R + 1)$$

Using the constraints  $P > 1$  ms,  $n \geq 11$ , and  $R = 1.6$  Mc/s, we obtain  $n > 11$ . A pair of primitive polynomials for 11-stage m-sequence preferred pairs is selected:  $h_1 = x^{11} + x^3 + 1$  and  $h_2 = x^{11} + x^9 + x^3 + 1$ , to generate Gold code sequences. Since bipolar non-return-to-zero codes exhibit strong anti-interference capability and are unaffected by channel characteristic variations, code elements 0/+1 are transformed to -1/+1.

## 3. PN-DOR Beacon Simulation Implementation

Based on the designed PN-DOR beacon simulation parameters, this chapter simulates the modulation of intermediate-frequency PN-DOR beacons, compares spectral differences between PN-DOR and DOR beacons, and references the VLBI data acquisition process to design observation frequency channels for extracting baseband PN-DOR beacons from intermediate-frequency simulation signals, followed by demodulation and decoding.

### 3.1 PN-DOR Modulation

According to CCSDS standards, spacecraft downlink signals employ a unified carrier TT&C system, where two DOR beacons are phase-modulated onto the downlink unified carrier, expressed as:

$$s(t) = \sqrt{2P_T} \sin[2\pi f_c t + \phi_1 \sin(2\pi f_1 t) + \phi_2 \sin(2\pi f_2 t)]$$

where  $P_T$  is the total downlink signal power,  $f_c$  is the main carrier frequency,  $\phi_1$  and  $\phi_2$  are modulation indices, and  $f_1$  and  $f_2$  are DOR beacon frequencies. In X-band, the two DOR beacon frequencies are  $f_1 = 3.8$  MHz and  $f_2 = 19.2$  MHz. Referencing the beacon parameters from the Chang'e-5 lunar mission, the X-band main carrier is designed as  $f_c = 8470$  MHz with modulation indices  $\phi_1 = \phi_2 = 0.4$  rad. Figure 6 [Figure 6: see original paper]a shows the DOR beacon spectrum.

Since one set of PN-DOR beacons is sufficient for delay ambiguity resolution and wider frequency spacing yields higher delay measurement precision, only the DOR tone at  $f = 19.2$  MHz requires spread-spectrum modulation. The downlink signal modulated with PN-DOR beacons becomes:

$$s(t) = \sqrt{2P_T} \sin[2\pi f_c t + \phi a(t) \sin(2\pi ft)]$$

where  $a(t)$  is the Gold code sequence and  $\phi$  is the modulation index (0.4 rad).

To reduce computational scale while preserving the original signal structure, simulation begins from digital intermediate frequency with a starting frequency  $f_d = 8445$  MHz. The downlink signal modulated with PN-DOR beacons can be expressed as:

$$s(t) = \sqrt{2P_T} \sin[2\pi(f_c - f_d)t + \phi a(t) \sin(2\pi ft)]$$

Using the PN-DOR simulation parameters designed in Section 2.3, a random Gold code sequence is selected and shaped through an RRC shaping filter with roll-off factor  $\beta = 0.25$  and span coefficient  $K = 32$ . The shaped Gold code sequence is then spread-spectrum modulated onto the DOR tone at  $f = 19.2$  MHz to obtain the final downlink signal modulated with PN-DOR beacons, as shown in Figure 6 [Figure 6: see original paper]b. A flat-bandwidth PN-DOR beacon is obtained at the carrier frequency  $f = 19.2$  MHz, transforming the traditional DOR single-frequency signal into a broadband signal of approximately 2 MHz bandwidth.

### 3.2 PN-DOR Extraction

Referencing the VLBI data acquisition process, baseband signals containing PN-DOR beacons are extracted from intermediate-frequency simulation signals for

subsequent demodulation and decoding. The extraction flow is illustrated in Figure 7 [Figure 7: see original paper].

Based on the amplitude-frequency characteristics of PN-DOR beacons, the observation frequency channel is set to 2 MHz to filter the intermediate-frequency signal and extract signals within the corresponding frequency range. The channel-filtered signal is a real signal with symmetric frequency components in positive and negative frequency domains; direct frequency shifting would cause spectral aliasing. To avoid this, a Hilbert transform is first applied to retain only the positive frequency components. After frequency shifting, an inverse Hilbert transform restores the real signal. Finally, downsampling to baseband yields the baseband signal containing PN-DOR beacons.

Figure 8 [Figure 8: see original paper] shows the amplitude-frequency diagram of the baseband signal containing PN-DOR beacons. Within the observation frequency channel, the PN-DOR beacon spectrum approximates that of radio sources, enabling reduction of delay errors caused by equipment phase fluctuation effects through differential processing.

### 3.3 PN-DOR Demodulation and Decoding

Unlike conventional VLBI, which performs interferometric processing directly on baseband signals containing DOR beacons, baseband signals containing PN-DOR beacons require not only correlation processing but also demodulation and decoding to obtain Gold code sequences for post-processing tasks such as ambiguity resolution before deriving delay and delay rate.

The PN-DOR beacon demodulation process consists of coherent demodulation, low-pass filtering, and sampling decision. Coherent demodulation requires a local carrier strictly synchronized in frequency and phase with the received modulated signal. Since linear-phase filters used during intermediate-frequency signal extraction and baseband conversion alter signal phase, phase compensation is necessary. The compensation phase  $\psi_{fir}$  is:

$$\psi_{fir} = \pi f_b (N - 1) \Delta T$$

where  $N$  is the linear filter order,  $\Delta T$  is the sampling interval (the reciprocal of the intermediate-frequency signal sampling rate), and  $f_b$  is the baseband carrier frequency. With an observation frequency channel of 2 MHz,  $f_b = 1$  MHz, and the coherent carrier becomes:

$$c(t) = \sin(2\pi f_b t - \psi_{fir})$$

Multiplying the coherent carrier with the received modulated signal and passing through a low-pass filter extracts the low-frequency component. A decision threshold of 0 is then set for sampling decision and demodulation. Due to noise

interference during transmission, direct decoding exhibits a certain bit error rate; therefore, the receiver must generate a spreading code with the same phase as the received code sequence for correlation calculation to achieve decoding.

This experiment employs the sliding correlation method. The decoding flow is shown in Figure 9 [Figure 9: see original paper]. The receiver sets up an identical Gold code sequence generator as the transmitter, selecting any  $m$ -sequence and cyclically shifting it backward by  $i$  bits (where  $i = 1, 2, 3, \dots, 2047$ ) to perform modulo-2 addition with another  $m$ -sequence, generating the  $i$ -th Gold code sequence for correlation calculation with the received code sequence. When the local Gold code sequence matches the phase of the received sequence, a correlation coefficient peak appears, allowing determination that the transmitted sequence is the local Gold code sequence producing the peak, thus achieving decoding.

Figure 10 [Figure 10: see original paper] shows the PN-DOR decoding results, with the horizontal axis representing the local  $i$ -th Gold code sequence and the vertical axis showing the correlation coefficient between the local Gold code sequence and the received sequence. A unique correlation peak appears during sliding correlation decoding, enabling determination that the transmitted sequence is the local Gold code sequence producing the correlation peak.

## 4. Impact of Spectral Aliasing on PN-DOR

Building upon the simulation analysis of PN-DOR beacon encoding, modulation, extraction, demodulation, and decoding, this chapter further investigates potential spectral aliasing phenomena in future deep space exploration missions. Simulation scenarios with varying degrees of spectral aliasing between two PN-DOR beacons are conducted to analyze the impact on target PN-DOR beacon extraction, demodulation, and decoding.

### 4.1 Principle Analysis of Spectral Aliasing

According to frequency bands allocated by the International Telecommunication Union for deep space exploration, the X-band frequency range is 8400–8500 MHz [1], and TT&C downlink signal channel resources are limited. As deep space exploration missions advance and the number of spacecraft increases, mutual interference between different spacecraft beacons becomes inevitable. In practical engineering missions, multiple PN-DOR carriers are typically arranged rationally to avoid interference from spectral aliasing. Moreover, each spacecraft signal has an independent phase center, and correlation processing handles PN-DOR signal data separately according to different phase centers, enabling acquisition of interferometric fringes even under spectral interference. The ability to correctly decode Gold codes for ambiguity resolution under spectral aliasing conditions provides strong support for PN-DOR beacon application in VLBI orbit determination.

PN-DOR beacons are signals with certain spectral bandwidth. If an X-band

PN-DOR beacon has a bandwidth of 2 MHz and two PN-DOR beacons with center frequencies  $f_1$  and  $f_2$  are received within the same antenna beam, spectral aliasing and mutual interference occur when  $|f_1 - f_2| < 2$  MHz.

Two Gold code sequences are randomly selected, shaped through an RRC filter, and spread-spectrum modulated onto DOR beacons at frequencies  $f_1 = 19$  MHz and  $f_2 = 18$  MHz, respectively, resulting in 1 MHz spectral aliasing between the two PN-DOR beacons (50% aliasing rate). Simulation results are shown in Figure 11 [Figure 11: see original paper]. Figure 11a shows the two PN-DOR beacons before spectral aliasing, while Figure 11b shows the aliased spectrum, where the overall spectral bandwidth widens to approximately 3 MHz.

Assuming the observation target is the PN-DOR beacon with a spacecraft carrier frequency of 19 MHz and an observation frequency channel bandwidth of 2 MHz, the baseband signal extraction flow from Figure 7 is followed. Based on the observation target, the observation frequency channel is designed, and the intermediate-frequency signal undergoes bandpass filtering, Hilbert transform, frequency shifting, inverse Hilbert transform, and downsampling. The amplitude-frequency diagram of the extracted baseband signal is shown in Figure 12 [Figure 12: see original paper]. Compared with Figure 8, the extracted baseband signal spectrum exhibits aliasing from other beacons on the left side, indicating interference.

## 4.2 Experiments on Impact of Spectral Aliasing on PN-DOR

The demodulation and decoding processes for PN-DOR beacons under spectral aliasing scenarios are identical to those for single PN-DOR beacons. A coherent carrier strictly synchronized with the received modulated signal is generated locally for coherent demodulation. Although the target PN-DOR beacon experiences strong interference due to spectral aliasing, the receiver's Gold code sequence generator produces a spreading code with the same phase as the received code sequence through cyclic shifting. When the two sequences undergo correlation calculation, a correlation coefficient peak appears, restoring the interfered information sequence into a complete, error-free Gold code sequence.

By adjusting the relative carrier frequency distance between the two PN-DOR beacons, the degree of spectral aliasing can be varied. Figure 13 [Figure 13: see original paper] shows PN-DOR decoding results under different spectral aliasing degrees. Figures 13a, 13b, and 13c demonstrate that despite increasing spectral aliasing, correlation peaks consistently appear during sliding correlation decoding between the received sequence and local Gold code sequence, enabling correct decoding.

Even when two PN-DOR beacons completely overlap in spectrum, they can still be decoded correctly. As shown in Figure 13d, when the received sequence correlates with two local Gold code sequences, both correlation coefficients approach 0.5, significantly higher than those of other sequences. This allows determination that the information sequences transmitted by these two beacons are the

local Gold code sequences producing the correlation peaks. Therefore, PN-DOR beacons can correctly decode Gold code sequences even under spectral aliasing conditions.

## 5. Conclusion

This paper investigates a new type of beacon—PN-DOR—based on spread-spectrum modulation of DOR beacons using Gold code sequences. By replacing traditional single-frequency signals with continuous-spectrum signals of certain bandwidth, PN-DOR beacons approximate radio source signal spectra, reducing measurement delay errors caused by equipment phase fluctuation effects and substantially improving group delay measurement precision for deep space spacecraft VLBI.

Referencing Chang'e-5 VLBI beacon parameters, this paper introduces PN-DOR beacon parameter design requirements and methods. Using a 2 MHz radio source observation bandwidth as an example, a set of PN-DOR beacon simulation parameters is designed. Simulations of PN-DOR beacon encoding and modulation are conducted, with comparative spectral analysis between DOR and PN-DOR beacons. Referencing the VLBI data acquisition process, baseband signals containing PN-DOR beacons are extracted from intermediate-frequency simulation signals, followed by demodulation and decoding to facilitate subsequent ambiguity resolution processing. Scenarios of spectral aliasing between two PN-DOR beacons are simulated to analyze the impact on PN-DOR beacons. These efforts establish a foundation for future PN-DOR beacon applications.

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