Design and Practice of Communication System During EDL for Mars Probe

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Abstract. Tianwen-1 Mars exploration mission is a mission for China to "Orbit, Fall and Patrol" Mars though a launch. Entry, descent and landing (EDL) of Mars exploration mission is one of the most important links in the whole mission process. Based on the characteristics of relay communication task in this process, this paper introduces the relay communication system scheme and key technology of Tianwen-1 Mars probe to adapt to the characteristics of complex timing, high autonomy, black barrier phenomenon and high dynamics of EDL segment communication task. At the same time, combined with the landing mission of Tianwen-1, the in orbit verification of relay communication in EDL is summarized and analyzed. The relay communication scheme proposed in this paper successfully supports the relay communication mission of the EDL section of the Mars Exploration of Tianwen-1.

Keywords: Tianwen-1 Mars probe · Entry descent and landing (EDL) · relay communication system

1 Introduction

As the first Mars probe in China, Tianwen-1 has realized the exploration mission of "circling, landing and patrolling" Mars through one launch. The Tianwen-1 Mars probe consists of an orbiter and a landing rover, which consists of an entry module and a Mars rover.

The entry, descent and landing (EDL) phase of the Mars exploration mission is one of the most important links in the whole mission process. In this stage, the detector completed complex high dynamic maneuvers such as high-speed aerodynamic deceleration, parachute deployment, and back cover removal in a short time, which is the most difficult and risky stage of Mars exploration mission. The EDL communication is the only approach to understand the working status and health of the lander during the important process from separation of the two vehicles to landing on the surface of Mars. The relative distance between the lander and the earth in the EDL segment is generally 109 km, and the communication signal to the earth is very weak, with a one-way delay of about 20 min. The experience of previous Mars landing missions abroad shows that, Reliable communication links play a vital role in monitoring the flight status of the ground probe,

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the process of aerodynamic deceleration, the key information of parachute deployment and lander landing on the Martian surface, and providing flight decisions.

To ensure the implementation of the communication scheme, Geometric visibility between two detectors, Opportunity to enter the Martian atmosphere, Entry method, And the orbit and attitude of the Orbiter in the EDL process. All conditions constrain the scheme design. Therefore. EDL phase communication scheme and technical approach design are closely combined with the actual implementation of Mars exploration mission, The communication link is designed around the timing of the task; Meanwhile, The function, performance and equipment configuration of the communication system are all carried out for the purpose of uninterrupted communication throughout the whole process and to ensure the reliability and stability of the communication link.

This paper introduces the scheme design and in orbit verification of the EDL relay communication system of the Tianwen-1 Mars probe.

2 Task Characteristics

2.1 Task Difficulty

1) Complex time series

The landing phase of the Probe mainly includes the pre-atmospheric entry phase and the EDL process. After seprating from the Obiter, the lander arrives at the entry point of the Mars atmosphere after going through a descent orbit of about three hours, enters the EDL segment of about 7-9 minutes, and then lands on the Mars surface. In a few minutes of EDL, many complex tasks, such as atmospheric entry, ejection parachute, backshell separation, base separation, landing platform and Mars vehicle landing have been carried out, which require the stability, reliability, continuity and autonomy of the communication link.

The flight key events sequence of the EDL is shown in Fig. 1.

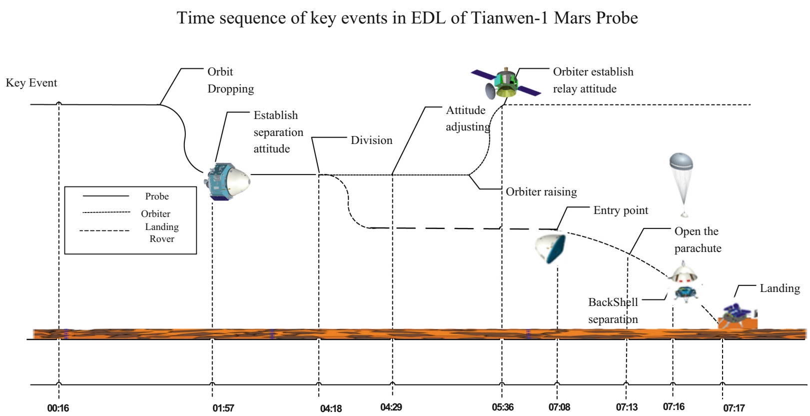

Fig. 1. Timing chart of key events in the EDL stage of Tianwen-1 Mars probe

2) Weak signal and large delay

The weight and power consumption of the Lander are constrained by a single launch task. It is not possible to configure large aperture high gain antenna and high power amplifier. Direct communication to the ground is facing huge space loss, and the received signal on the ground is very weak. During the EDL mission, the lander was approximately 300 million kilometers from the ground with a delay of more than 30 min. Large latencies cause EDL critical task segments to be in a fully autonomous “uncontrolled” phase.

3) High Doppler Dynamics

Actions in the EDL process result in a very high Doppler dynamic overlay on the communication signal, and the Doppler range and Doppler rate of change are very large. High Doppler dynamics in the EDL process can easily cause the receiver loop to be unlocked, resulting in data loss. It is difficult to achieve high dynamic tracking and high sensitivity receiving demodulation for transceiver at the same time, which puts forward higher requirements for electronic instrument design and system design.

4) Black Barrier Phenomenon

The Landing Rover enter the Mars atmosphere at hypersonic speeds, High temperatures around the Probe caused by a sharp deceleration in a short period of time ionize atmospheric molecules and some ablative materials, Form plasma sheath, The plasma sheath absorbs and diffuses electromagnetic waves seriously, thereby creating communication blackout. The blackout phenomenon is related to the shape of the probe, speed, flight angle of attack, heat-proof material and atmospheric density.

In 1997, the Mars Pathfinder encountered a 30-s signal interruption during its landing [1], Mars Curiosity encountered a similar situation when it landed in 2012 [3], Curiosity had a signal drop of 30–40 dB during EDL.

The disruption of communication signals during the EDL is a fatal threat to the safety of landing task. Therefore, it is necessary to rationally design the flight trajectory and speed, and take necessary measures to mitigate or avoid the impact of the blackout on the communication link.

2.2 Brief Summary

Considering the above challenges, the design of communication systems has the following requirements:

1) The Lander is separated from orbiter in Mars orbits. During EDL, it need to communicate through relay communication links with orbiter, to sending Earth-to-lander commands and receiving telemetry data during the process.
2) In the process of Entering the Mars atmosphere, parachuting, Backshell separation, and landing, The Lander will have a large angle posture change, According to the motion process and attitude change, it is necessary to design the lander antenna installation position, antenna beam, communication link channel parameters, so that the two antennas can point to each other, and the communication link remains uninterrupted during the process.

3) After the parachute and the backshell are separated, There is a relay and switching process between the lander's entry module and the Mars vehicle's communication equipment and antenna, We need to schedule the device switches and radio frequency signal transmission and reception, to ensure reliable switching and continuous communication.

3 EDL Communication System Design

3.1 Communication Process

Before separation, Lander and Orbiter begin to provide UHF band communication link. After separation, The Orbiter enters relay track, The Lander establish UHF band relay communication link with the Orbiter to maintain contact with the Earth from entry point to landing, The whole process takes about 3 h, EDL process takes about 7–9 min, Communication distance in the range of 600–1000 km.

The communication link of the Tianwen-1 task is in Fig. 2, The relay communication in EDL shows in Fig. 3.

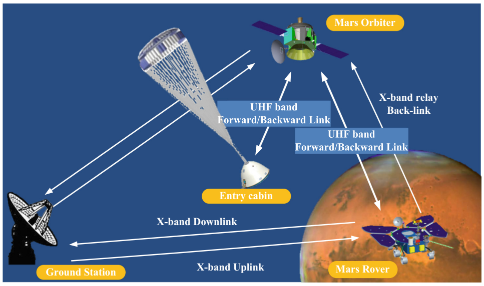

Fig. 2. Tianwen-1 Probe communication Links

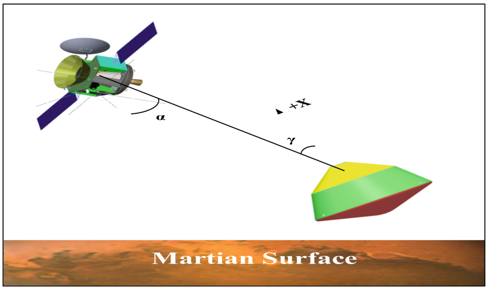

Fig. 3. Relay communication in EDL

3.2 Design of Relay Communication System

3.2.1 System Configuration

Tianwen-1 relay communication system consists of the following equipment: UHF transceiver of entry module and Mars rover, Backshell antenna and UHF relay antenna for Mars rover, UHF relay communicator, UHF band relay receiving/transmitting antenna of the Orbiter, etc.

Figure 4 is the design schematic diagram of the Probe relay communication system.

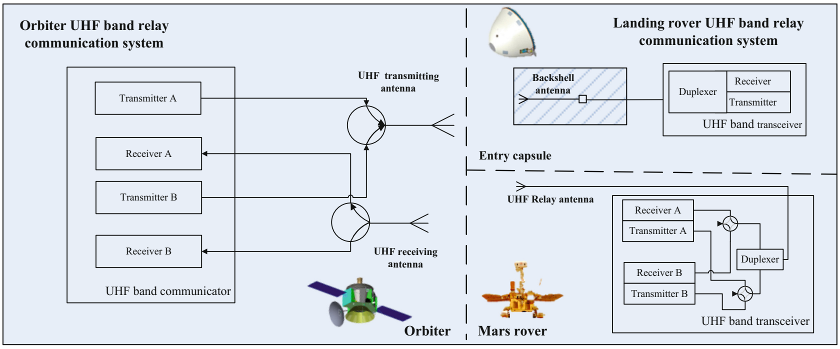

Fig. 4. Schematic diagram of relay communication system

3.2.2 Technical Indicators

1) System and communication protocol

According to the characteristics of the task, the relay communication protocol of Tianwen-1 Probe selects CCSDS Proximity-1. The physical layer of the protocol is UHF band. The protocol link features short delay, medium strength signal, short independent dialogue [4].

In the full duplex mode, the protocol first completes the request or negotiation process between the two communication parties at a lower rate through the handshake channel, After confirming various channel parameters, establish the service communication channel. Communication link can be adaptive, The channel, coding and code rate can be adaptively adjusted according to the signal quality. The data transmission uses the standard format of Proximity-1 link protocol, Automatic repeat request mechanism and sequence control service, Use 32 bit CRC check to establish two-way reliable connection.

The protocol uses ARQ automatic retransmission mode for data transmission, to ensure the reliability of data transmission. Use signal to noise ratio (Eb/N0) estimation method to achieve adaptive code rate switching, to improve bit error performance. It can support 8 forward rates (1–64 kbps) and 12 backward rates (1–2048 kbit/s) of circular adaptive switching. Figure 5 is the schematic diagram of the communication parameter switching process through the signal to noise ratio estimation method.

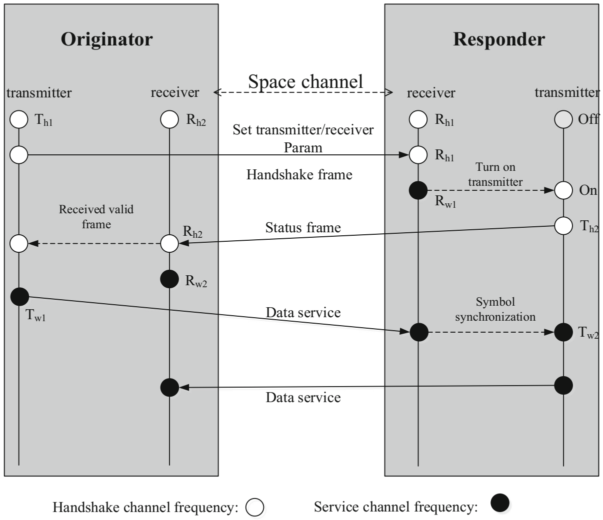

Fig. 5. Autonomous switching process of communication parameters

3.2.3 Working Status

With different communication capabilities and mission requirements, the working status of relay communication system can be full duplex, half duplex and simplex [5]. Table 1 shows carrier frequencies of forward and backward signals of relay communication.

Table 1. Carrier frequency of relay communication link

Channel number	Forward frequency(MHz)	Return frequency (MHz)
Handshake channel	435.6	404.4
Service channel 1	437.1	401.585625
Service channel 2	439.2	397.5
Service channel 3	444.6	393.9

In the full duplex working state of the relay communication system, the call process uses the handshake channel, and the communication process uses the service channel; In the simplex working state, the working channel is used.

To ensure link stability and timeliness, The relay link in the EDL section of Tianwen-1 adopts the simplex state in the above protocol. After landing on Mars, the communication between the rover and the orbiter is in full duplex working state.

3.2.4 Signal Modulation and Coding

Manchester code is used to PM modulate the residual carrier for the inter communication signal in UHF band, The modulation method is suitable for bandwidth unrestricted, short distance, low bit rate transmission.

The mathematical form of this modulation mode is:

$$s(t) = \sqrt{2P_t}\sin(\omega_c t + \beta m(t) + \theta_c) \quad (1)$$

In the formula, P_t is the available transmitter power; ω_c is the carrier angular frequency, β is modulation index, θ_c is the tracking carrier phase, m_t is data modulation.

For Manchester code, P_t is the unit square wave waveform, Because of the digital property of m_t:

$$s(t, \theta_c) = \sqrt{2P_t}\cos\beta\sin(\omega_c t + \theta_c) + \sqrt{2P_t}\sin\beta m(t)\cos(\omega_c t + \theta_c) \quad (2)$$

It can be seen from (2) that,

When modulation index $\beta = \pi/2$, the carrier component is 0, thus,

$$s(t) = \sqrt{2P_t} m(t)\cos(\omega_c t + \theta_c) \quad (3)$$

That is, ordinary BPSK modulated signal.

When modulation index $\beta < \pi/2$, the carrier component is not 0.

Therefore, less than$\pi/2$ is used in relay communication (β = Modulation index of 1.05), It makes effective separation of modulated signal and residual carrier, It is convenient to extract and track carrier signals with low SNR; Meanwhile, according to the characteristics of Manchester code (Map a symbol to a pair of [1, −1] or [−1, 1] sequences), Get the energy integration of modulated signal, Integrating obtains two phases of information, which is coherently accumulated with the local frame synchronization header, Obtain SNR estimation results, and decide if the threshold is exceeded. Then discriminate current data transmission energy and code rate, to achieve adaptive estimation and demodulation.

Relay communications use (7, 1/2) convolution codes as channel encoding, about 4.5 dB channel coding gain can be obtained at error rate of 10^6.

3.3 Communication Link Design

3.3.1 Pointing and Visibility Analysis

EDL relay link uses UHF band antennas and instruments for both-way communication. UHF band relay antenna has two beam ranges of ±30° and ±80°, antenna gain varies greatly in different beam ranges, Therefore, the coverage of inter- communication link needs to be analyzed in combination with the attitude and orbit characteristics of the two devices during the task.

The angular relationship between the two probes after the separation and the separation of backshell is illustrated in Fig. 6. In the diagram, the angle α is the angle between two geometric centers and the mechanical axis of the Orbiter. The γ Angle between the geometric center line of the two vehicles and the mechanical axis of the lander. As the flight progresses, from the two probes are separated on orbit until the lander enters the atmosphere, γ Angle remains within antenna coverage, From entering the atmosphere to landing, A series of actions result in an unstable entry posture, γ appears irregular changes. The simulation curve is shown in Fig. 6.

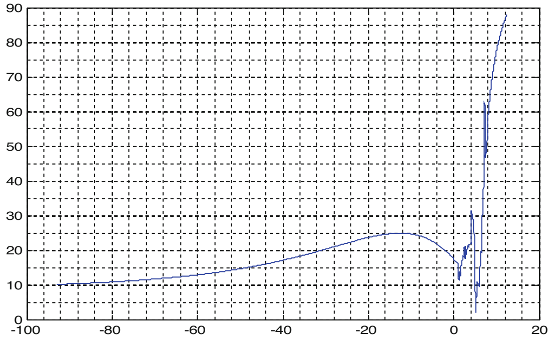

Fig. 6. Simulation analysis of antenna pointing in EDL

3.3.2 Channel Design

In EDL, Both UHF-band transceivers are working in a single mode, Forward and backward link code rates are 1 kbps and 2 kbps, The channel key indicators are analyzed below.

1) **Capture and demodulation threshold**

The carrier-to-noise ratio of the communication link is analyzed as follows:

$$\mathrm{C}/N_0 = [\mathrm{P_C}] - [\mathrm{N_0}] = [\mathrm{P_C}] + 174 - [\mathrm{N_F}] \tag{4}$$

Where, N_F is the noise factor, P_C is carrier power。When the noise figure is 3.5dB and the carrier capture threshold reaches -140 dBm, the C/N0 is 30.5dB/Hz, which makes the system possible.

For data demodulation, When the code rate is 1 kbps, the demodulation threshold is -126 dBm, Signal power can be calculated according to the formulas (2) and (4), According to the carrier-to-noise ratio andE_b/N_0,the result as follows (Noise Figure is 3.5):

$$C/N_0 = P_t \sin^2 \beta + 174 - 3.5 = 43.26 \text{ dB/Hz} \tag{5}$$

$$E_b/N_0 = [C/N_0] - [R_b] = 13.26 \text{ dB} \tag{6}$$

Therefore, when the channel error rate $P_e = 1 \times 10^{-6}$, there is still a 2.66 dB margin relative to the theoretical signal-to-noise ratio of 10.6 dB, and the system can be implemented.

2) **Channel Margin**

According to orbit parameters and communication indicators, Channel budget for communication links during EDL is shown in Table 2.

Table 2. Relay communication link margin in EDL

Sequence number	Channel	CodeRate(bps)	Relay communication antenna	Channel Margin(dB)
1	Forward	1k	Orbiter transmit antenna→Backshell antenna	8.43
2	Backward	2k	Backshell antenna→Orbiter Receiving Antenna	4.78
3	Forward	1k	Orbiter transmit antenna→Rover Relay Antenna	20.43
4	Backward	2k	Rover relay Antenna→Orbiter receiving Antenna	16.78

From Table 2, in order to keep a certain signal-to-noise ratio margin, to cope with large fluctuations and jumps in signals caused by complex flight conditions in the EDL phase, considering large channel margins when designing communication links is necessary.

4 On-Orbit Practice

On May 15, 2021, the Mars Explorer Tianwen-1 separated its two spacecraft in orbit. Lander experienced nearly 3 h of off-track landing, and EDL segment "Black 9 min", Successfully landed on the Utopian Plain of Mars. During the whole EDL task, the relay communication system works stably and reliably, and the communication link is uninterrupted throughout the whole process.

4.1 Received Signal Power and Doppler Dynamics

During separation from the Orbiter to landing on Mars, The change of signal power received by the UHF transceiver for the lander (Entry module + Mars Vehicle) is shown in the red curve in Fig. 7. Before entering the Mars atmosphere, communication link remains stable, The signal power steadyly change between −95 dBm and −122 dBm. Large fluctuations in signal strength occur when entering the Mars atmosphere, Combined with the analysis of working sequence, the changes of distance between two vehicles after entering, the effect of blackout caused by plasma sheath on signal, the changes of large angle attitude of lander caused by parachute, separation of backshell, and the channel changes caused by antenna index after Mars vehicle relay can be corresponded to.

Comparison of signal power received from on-Orbit relay link with design results, the performance index under different antenna beam angles is analyzed, and the actual pointing and coverage of two relay antennas during EDL can be obtained. The actual signal strength results are good to verify the correctness of the simulation results of antenna pointing.

The blue curve in Fig. 7 shows the change of doppler frequency offset in orbit in EDL. Before entering the Mars atmosphere, due to the lander's stable speed direction and attitude, the Doppler frequency offset is relatively small, varying from 0.1 to 0.6 kHz. From the point of atmospheric entry, with the change of velocity and posture, the Doppler dynamic changes sharply, and the frequency offset increases from 0.1 kHz to ±6 kHz. During this process, the forward-backward link of relay communication remains continuous, and the UHF transceiver receives stable loop tracking without losing lock, which enables the organic combination of high dynamic tracking and high sensitivity demodulation.

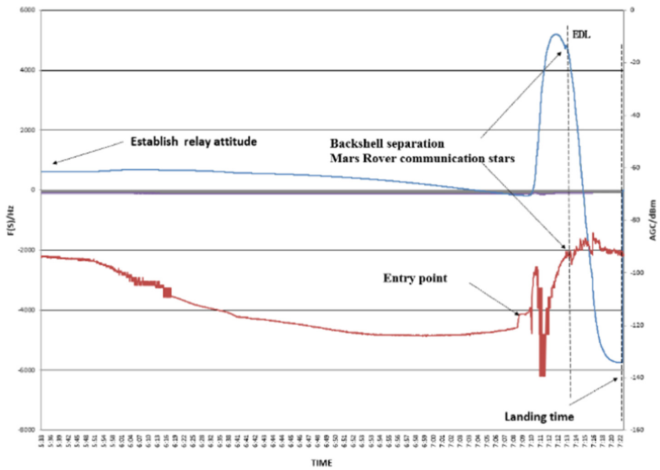

Fig. 7. Signal strength and Doppler shift during EDL

4.2 Black Barrier Impact

After entering the Mars atmosphere, electromagnetic waves around the lander are affected by plasma sheaths, creating a "black barrier phenomenon". Figure 10 shows the signal level of the relay link before and after the lander enters the Mars atmospheric point. As can be seen from Fig. 7, the signal received fluctuates significantly about 100 s after entering the atmosphere of Mars, Maximum signal jitter causes a sharp decrease in signal strength from −98 dBm to −139 dBm, which is about 40 dB.

In the design process, combining the aerodynamic profile of the landing patrol, flight trajectory, and atmospheric density after entering the Mars atmosphere, the simulation of electron number density in plasma sheath is carried out. The results are shown in Fig. 8. Simulation results show that,during the entry process, the electron number density increases and then decreases, and reach the maximum at around 95 s, about $16 \times 10^{13}/\text{m}^3$. The time when the maximum electron number density occurs corresponds to the time when the power of the communication signal between the orbiters fluctuates sharply. In the actual EDL process, the distribution of plasma sheaths is not static, it changes in both spatial and temporal dimensions. For this complex time-varying communication environment, In the simulation system, the influence of PSK signal with Manchester code is analyzed by establishing the dynamic model of electron density.

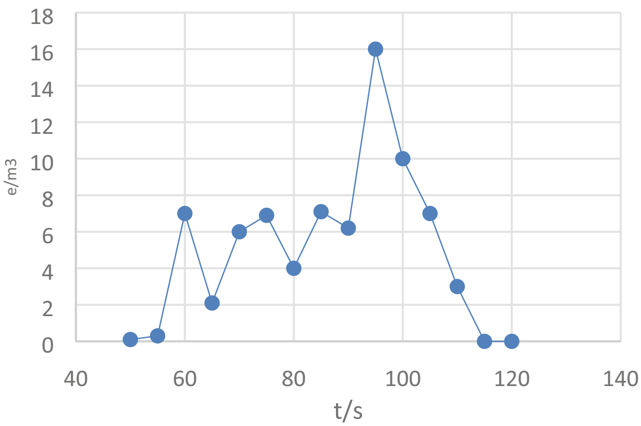

Fig. 8. Variation of electron number density in plasma sheath

According to the synchronous lock state in Fig. 9, Carrier and frame synchronization are locked during blackout, the communication link is uninterrupted, The Lander continuously sends telemetry data to the Orbiter. This means that in the communication channel calculation model, Margins still exist due to channel parameters such as antenna pointing accuracy, antenna performance indicators and transmission power, etc. Real datas of relay communication link in the impact of blackout can be used in subsequent Mars or other atmospheric planet missions, and correction of communication simulation model in Plasma Sheath of Blackout Process.

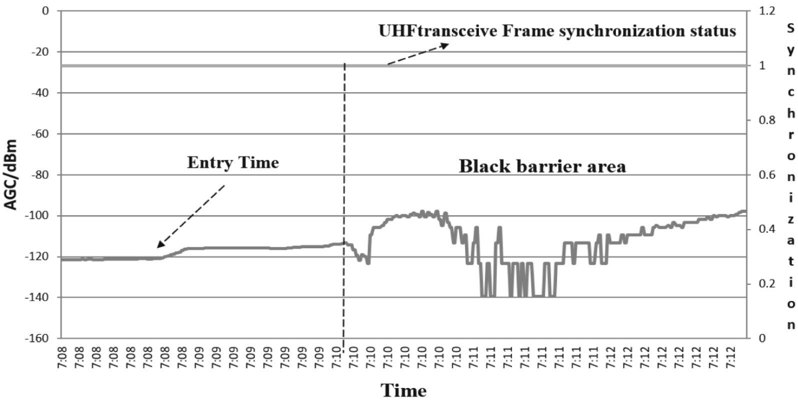

Fig. 9. Communication link affected by black barrier in EDL

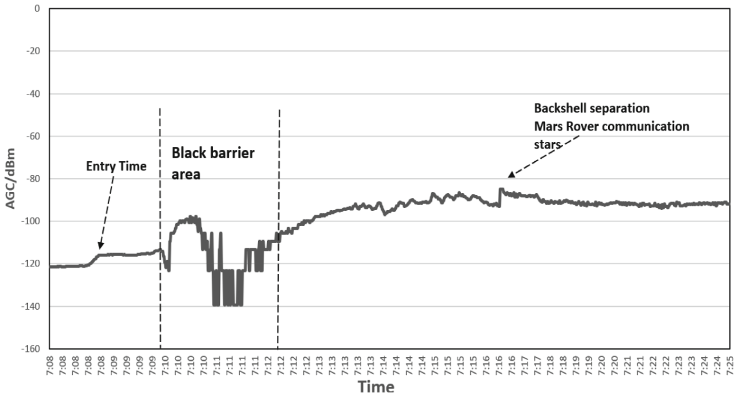

Fig. 10. Communication relay before and after back shell separation in EDL

4.3 Communication Link Switching

In the EDL, two minutes after entry, the parachute unfolds, and the backshell antenna separates with the backshell. At this time, the reley communication link is switched from the cabin to the Mars vehicle in real time, so as to achieve the relay link communication of the cabin. The change of signal strength during switching is shown in Fig. 10. We can see that, the signal strength received by Mars Vehicle is about 9 dB higher than that of the entry compartment, this matches the design status of both antennas and electronic instruments.

5 Summary and Revelation

As the engineering practice of the relay communication task of China's first Mars exploration mission, from the perspective of system optimization, the relay communication system has been designed and validated, from the overall design level to the electronic instruments technological approach according to the task characteristics of EDL. The system is stable and reliable to support the relay communication during the whole entry, descent and landing process. At the same time, in the following work on Mars surface, ensures the relay communication and data transmission tasks with the Orbier effectively.

The design and on-orbit verification of the EDL relay communication system for the Tianwen-1 Mars Explorer has accumulated valuable research and engineering experience, which provides useful reference value and support for the subsequent Chinese interplanetary and deeper space exploration missions. At the same time, through this successful experience, we can also get the following inspiration:

1) In order to achieve the communication process in EDL, considering the characteristics of the mission, and considering the factors such as orbit, probe attitude and communication system capabilities, various technical measures and paths should be reasonably selected to meet the requirements of the tasks for communication system.
2) EDL relay communication uses single-work communication mode in tasks. Based on the practical experience on-orbit, the full-duplex autonomous mode in the protocol can be considered in the future, and the link margin can be used rationally to improve the quality and data capacity in this process.
3) The practical data and experience of blackout zone communication, and cabin relay communication in the mission can be used to revise the parameters of the current simulation verification system, improve the system performance, and create a better technical basis for the subsequent deep space exploration missions.

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