



Research on Tianwen-1 Mars Probe Relay Communication Technology

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Abstract. As an important part of China's first Mars exploration mission, Tianwen-1 Mars probe relay communication system is responsible for supporting the capability of whole process communication self-management between the rover and orbiter, such as autonomous relay communication link establishment and communication parameters self-adaptive change mechanism. In the view of the limited resources and communication capacity of the rover and relay link, the X-band relay communication scheme is proposed for the first time in the world, which forms a backup with the UHF-band link to realize the relay communication at multi-node of the Mars relay orbit. In this paper, the UHF/X dual band relay communication system of Tianwen-1 Mars probe is firstly introduced, including the method of system design, relay communication protocol and operating mode are given. Finally, the results of on-orbit flight data are analyzed. The flight results show that the relay communication system of Tianwen-1 Mars probe successfully achieves the exploration mission objectives. Meanwhile, the system design, implementation and application can provide a technical reference for the China's deep space relay communication system in the future.

Keywords: Tianwen-1 Mars probe · deep space exploration · relay communication

1 Introduction

Mars is one of the important targets of human deep space exploration in the future. The establishment of efficient and stable communication links between earth and Mars is an important prerequisite and basic guarantee for the successful completion of Mars exploration missions. The deep space relay communication technology with high communication capability and low communication cost is regarded as the preferred solution to provide EDL (Entry, Descent and Landing) and Mars surface relay communication service to the Mars probe.

The NASA has proposed the idea of Mars relay communication network, which plans to launch multiple Mars orbiters carrying UHF-band relay communication equipment to realize the data communication between the Mars lander

and the orbiter. Nowadays, the Mars relay network consists of the Mars Odyssey, the Mars Reconnaissance Orbiter (MRO), and Mars Express. The establishment of the Mars relay communication network enhances the deep space probe all-weather communication capability, obtains the efficient data return capability, and reduces the Mars lander's mass and power limitations [1].

At the same time, the space data system advisory committee (CCSDS) formulated the Proximity-1 space link protocol according to the characteristics of the inter-satellite relay communication mission scenario. The UHF-band relay communication system of Tianwen-1 adopts the Proximity-1 protocol, and uses the automatic repeat queuing (ARQ) mechanism of the protocol to ensure the accuracy and efficiency of information transmission. In the future, with the development of the unified space data link protocol (USLP), it is expected to unify the all link protocols, and guide the inter-satellite relay communication in various frequency bands.

As China's first spacecraft to explore Mars, Tianwen-1 Mars probe has completed the Mars exploration mission of "orbiting, landing and roving" all in one journey. The Tianwen-1 Mars probe consists of an orbiter and a lander-rover combination. After launch, the probe will undergo the flight phase of earth-Mars orbit transfer, Mars braking and capture, orbiting Mars, and EDL.

After landing, the rover will conduct scientific exploration, and establish a relay communication link with the orbiter to transmit the exploration data. The areocentric orbit period is about 8.27 h, and the communication distance varies from 265 km to 15000 km.

Due to the large elliptical relay communication orbit of the Tianwen-1 Mars probe, the communication distance varies widely and is limited by the attitude of orbiter, the relay communication control cannot be completed in the real time. The probe relay communication system has high requirements on link autonomy and reliability. In view of the above characteristics, Tianwen-1 Mars probe proposed a multi-node and multi-system relay communication system scheme, which alternates the far-Mars arc and near-Mars arc to build a communication link, and the transmission link of X-band and UHF-band operates selectively, so as to realize the relay communication of deep space exploration data with high speed, efficiency and large capacity. In this paper, the design of the Tianwen-1 Mars probe relay communication system is introduced, and the key technologies are analyzed, and the communication link design is presented. Finally, the in-orbit flight test results are analyzed.

2 Design of Tianwen-1 Mars Relay Communication System

2.1 System Configuration

The orbiter and the lander-rover are integrated in the launch phase, earth-Mars transfer phase and Mars capture phase. The ground TT&C systems realizes the control and state monitoring of the lander-rover by the wired communication

through the orbiter, and the lander-rover has no requirement of RF measurement and control data transmission link. After the landing on the surface of Mars, the ground TT&C systems can control the lander-rover, monitor its status and transmit service data through the orbiter UHF-band relay communication link, or through the X-band Mars-earth communication downlink. In addition, lander-rover provides the bidirectional coherent carrier Doppler tracking beacon, and the Doppler information extracted by the orbiter is used for mutual positioning for mutual positioning between the rover and orbiter during the relay data communication.

The relay communication system of the Tianwen-1 Mars probe is composed of the orbiter relay communication subsystem and lander-rover TT&C system. Among them, the lander-rover TT&C system is composed of X-band communication equipment and UHF-band relay communication equipment. The orbiter relay communication subsystem is composed of X-band communication unit and UHF-band communication unit. The composition of Tianwen-1 probe relay communication system is shown in Fig. 1.

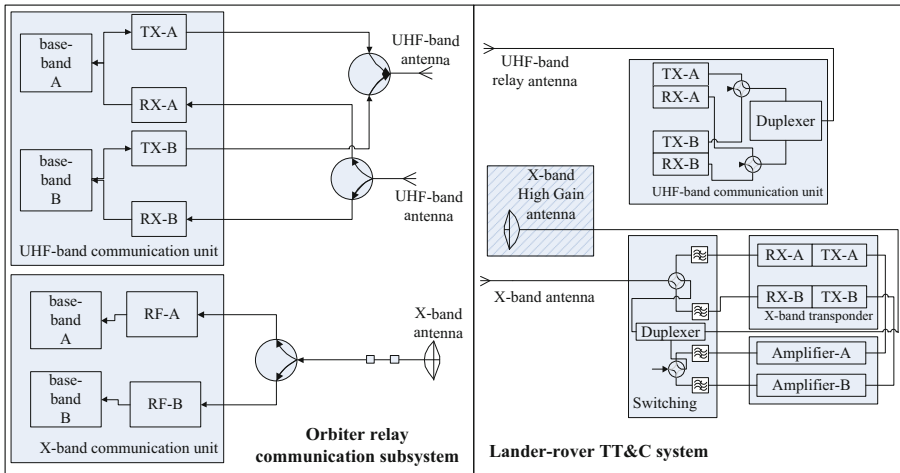


Fig. 1. Configuration of Tianwen-1 Mars probe relay communication system.

2.2 Design of Operation Mode

In the phase of Mars surface exploration, the Tianwen-1 Mars probe relay communication system is in a regular operation mode, and the rover establishes a bidirection relay communication link with the orbiter through the UHF-band transceiver and UHF-band antenna. In addition, as a complement to the relay communication in the UHF-band, the rover establishes a unidirection (rover-to-orbiter) X-band communication link with the X-band deep space transponder and X-band high gain antenna. See Table 1 for the Tianwen-1 Mars probe relay communication system operation mode.

Table 1. Tianwen-1 Mars Probe relay communication system Operation Mode.

Operation Mode	Data Rate (encoded)	Carrier Frequency
UHF-band	forward: 1 kbps–64 kbps return: 1 kbps 2 kbps 2 kbps 4 kbps 8 kbps 16 kbps 32 kbps 64 kbps 128 kbps 256 kbps 512 kbps 1024 kbps 2048 kbps	forward: 435.6 MHz 437.1 MHz 439.2 MHz 444.6 MHz return: 404.4 MHz 401.585625 MHz 397.5 MHz 393.3 MHz
X-band	2048 bps 4096 bps 32 kbps 64 kbps 128 kbps 256 kbps 512 kbps 1024 kbps 2048 kbps	8400.062 MHz

2.3 Signal Modulation and Demodulation Scheme Design

The X-band relay communication link uses suppressed carrier modulation. The UHF-band relay link is implemented by Manchester coding assisted residual carrier BPSK modulation. Through the adoption of less than of $\pi/2$ (rad) modulation index, makes the signal spectrum in discrete component (residue) carrier, at the same time, the Manchester coding power spectral density at zero frequency is zero, residual modulation signal and carrier component can be effectively separated, through the filter and narrow bandwidth loop tracking, realize to the extraction of carrier tracking.

According to the characteristics of residual carrier modulation, the carrier is locked in *I*-branch and the information is locked in *Q*-branch by using Costas phase detection and tracking method, which avoids solving the problem of phase inversion of *I* and *Q*, and reduces the processing complexity. Through the multi-stage filter extraction module, the taps of each rate range are extracted, and all other information except the carrier is filtered out to realize the tracking of very low SNR.

Based on the characteristics of Manchester coding, the *Q*-branch signals on each rate tap are matched with correlation and energy integration, and the current transmission data rate can be judged without prior information through the cumulative judgment of positive and negative energy, so as to realize the adaptive estimation and demodulation of communication data rate.

2.4 Design of Trajectory Measurement

In the Mars surface exploration phase, the orbiter provides X-band DOR for VLBI observation from the ground station to complete angle measurement, and combines tone ranging to complete orbit measurement of the orbiter. The ground station uses SBI (Same Beam Interferometry) observation to place the orbiter and rover signals in the same antenna beam for relative positioning.

On this basis, the position of the rover can be determined by combining the communication Doppler changes between the UHF-band link providers of the two probes. The rover’s UHF-band transceiver provides the coherent forward channel to support orbiter extractor Doppler change data.

2.5 Channel Coding

The channel coding methods suitable for deep space communication mainly include convolution coding, R-S coding, turbo coding and LDPC. The Tianwen-1 Mars probe relay communication system adopts convolution coding as the channel coding method of UHF-band relay channel. The convolution coding (7, 1/2) recommended by CCSDS is adopted, and the channel coding gain of about 4.5 dB can be achieved at the BER of 1×10^{-6} .

X-band relay communication channel coding adopts R-S+ convolution coding, with (7, 1/2) convolution code as the inner coding and (255,223) R-S coding as the outer coding. At a bit error rate of 1×10^{-6} , the channel coding gain of about 7 dB can be achieved.

The Tianwen-1 Mars probe relay communication system includes UHF-band bidirectional communication and X-band unidirectional communication. For bidirectional communication in UHF-band, CCSDS Proximity-1 is used. This protocol is suitable for bidirectional short distance wireless communication between fixed or mobile nodes.

Considering the large delay characteristics of the communication between the rover and the earth, the ground station cannot inform it to send the wrong data transmitted by the communication system again in time. In order to ensure the timing and correctness of the command, telemetry and other data, it is necessary for the rover to automatically select the data that has not been correctly received for re-transmission.

Common ARQ systems can be divided into three categories: equal-stop ARQ, back-off N-frame ARQ, and selective re-transmission ARQ. As for the communication link, its transmission distance is short, signal transmission delay is small and signal attenuation is relatively small. At the same time, considering the resource limitation and storage space overhead of the Mars rover platform, the back-off N-frame ARQ scheme of error control processing is adopted to ensure the correctness of data transmission [2].

The ARQ protocol mainly includes the functions of error detection, receiver feedback, data re-transmission, and transmission timeout control. The sender automatically re-transmits the incorrect data according to the feedback from the receiver.

Specifically, after the transmitter sends a data frame, the receiver needs to reply a proximity link code-word (PLCW) if it successfully receives the data frame. PLCW contains the serial number information of the valid frame received by the receiver. The maximum sending interval of two PLCW is defined as 20 s. The sender checks whether the data frame is successfully sent according to the PLCW feedback from the receiver. If the data frame is not successfully sent, the sender needs to resend the data frame. In order to improve efficiency, the sender does not need to send the next frame after sending a certain frame and waiting for receiving PLCW of this frame.

The unidirectional communication link in X-band multiplexes the downlink resources of the rover, and its data format and communication protocol are consistent with the Mar-earth downlink, which belong to a non-ARQ system.

When a data error occurs in the X band relay link, the Earth station on-demand re-transmission mechanism is used.

2.6 Design of Link Data Rate

In view of the dynamic characteristics of the trajectory, the forward link design of the probe UHF-band supports 7 levels of data rates: 1 kbps, 2 kbps, 4 kbps, 8 kbps, 16 kbps, 32 kbps and 64 kbps, and the return link supports 12 levels of data rates: 1 kbps, 2 kbps, 4 kbps, 8 kbps, 16 kbps, 32 kbps, 64 kbps, 128 kbps, 256 kbps, 512 kbps, 1024 kbps and 2048 kbps.

In the periareon, the orbiter realizes bidirectional communication to the rover through UHF-band narrow beam ($\pm 30^\circ$), and adaptively switches the communication data rate according to the change of relay communication orbit. The implementation of the adaptive data rate scheme mainly includes the following technical approaches:

- 1) Signal averaging, SNR estimation and data rate switching mechanism automatic gain control (AGC) telemetry in the receiving channel can reflect the input signal size to a certain extent. However, when the signal power is below -105 dbm, thermal noise occupies the main proportion of the input power detected by the AGC module, and the change of the input signal power is difficult to cause significant changes in the telemetry level of the AGC. The signal power threshold is directly related to the power detection bandwidth of the AGC.
- 2) Design and implementation of SNR threshold for data rate switching communication systems with adaptive transmission capability usually take the SNR as the standard to measure the channel conditions. The receiver estimates the SNR in real time and compares the SNR with the threshold required by technical indicators to select the appropriate transmission data rate. Then, the appropriate data rate is fed back to the transmitter in the form of control messages. When the transmitter detects the relevant control message, it issues the control command at the correct time to switch the transmission data rate.

Therefore, in order to better react the level fluctuation of the weak signal and accurately evaluate the quality of the received signal, the design detects the SNR or carrier-to-noise ratio (C/N_0) of the input signal by means of digital signal processing.

In view of the characteristics of Manchester coding, the relay communication system is put forward a way based on Manchester coding minimalist SNR estimation algorithm, through the algorithm can achieve a very reliable solution to Manchester code fuzzy and auxiliary input frequency error, reduce the carrier tracking loop to reduce the loop into the lock time, At the same time, it only occupies very little hardware processing resources, and the working mechanism is as follows:

- 1) By using the characteristics of Manchester coding, the signal branch and noise branch are separated, and the SNR is estimated by the two branches, and the fitting method is adopted to obtain a more simplified estimation method.
- 2) The estimated SNR can be directly used as an important criterion for carrier synchronization assistance, which can complete the fast acquisition function of initial frequency offset and speed up the locking process when the tracking capability of carrier tracking loop is limited.

The design of X-band unidirectional communication link supports 9 levels of data rates: 2048 bps, 4096 bps, 32 kbps, 64 kbps, 128 kbps, 256 kbps, 512 kbps, 1024 kbps, and 2048 kbps.

3 Analysis of Relay Communication Link

3.1 Analysis of UHF-Band Relay Communication Link

In the periareon of exploration, there are at most two relay communication arcs in each Martian day, which are called type I arc and type II arc. Among them, the type I arc is that the periareon appears near the zenith direction of the rover during relay communication, and the type II arc is that the apoareon appears near the zenith direction of the Mars rover during relay communication. Among them, the type I arc appears in the local daytime of Mars, and the longest communication window is about 10 min. Due to the close distance between the two probes, the peak data rate of the return link can reach 2048 kbps (encoding), which can be used for transmission of engineering telemetry and large load data. Type II arcs occur at night on Mars, with a relatively long communication window of several hours. The range of relay communication distance in type I arc is 265 km to 3500 km, and that in type II arc is 5000 km to 15000 km.

In the communication window a of periareon, the UHF-band communication link is adopted by default. In the communication window of apoareon, X-band communication channel is adopted. During the Mars surface exploration phase, the communication mode between orbiter and rover is shown in Fig. 2.

UHF-band relay communication link uses two UHF-band devices for bidirectional communication. The forward link data rate of the channel is 2 kbps (encoding), and the return link data rate is 1 kbps to 2048 kbps (encoding). The maximum communication distance between the orbiter and rover can reach 15000 km. Due to the different antenna gains in different beam ranges of the UHF band relay antennas of the two devices, the maximum 15000 km communication can only be achieved within the ($\pm 30^\circ$) beam of the UHF-band relay antennas of the two devices. Therefore, the relay communication in the UHF-band cannot cover all the arc segment of type II. Figure 3 shows the UHF-band communication performance with different received power and data rate.

- 1) In type I arc segment (communication distance varies from 265 km to 3500 km), it can ensure that both the surround device and rover relay antenna in UHF band can relay normally within the range of ($\pm 80^\circ$), and the channel code is convolution coding (7, 1/2). The specific code rate is as follows:

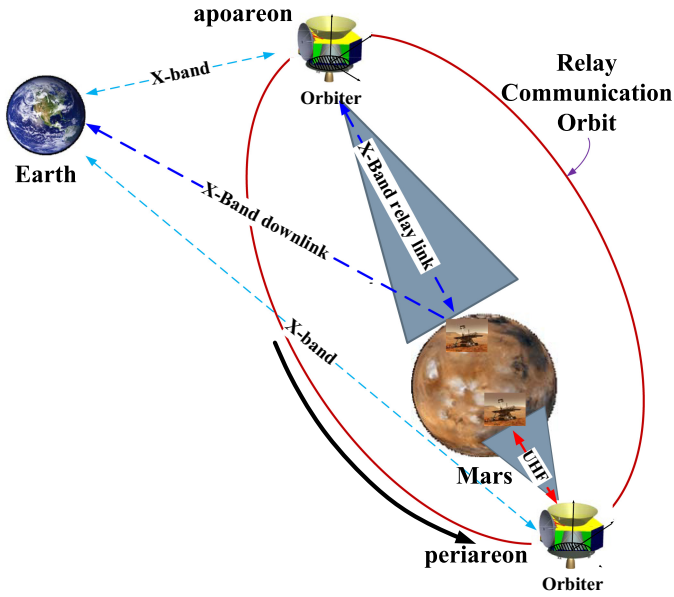


Fig. 2. Diagram of Tianwen-1 Mars probe relay communication link.

① When the communication distance is 265 km to 3500 km, the antenna beam angle of the two devices is within the range of $(\pm 80^\circ)$. According to the distance, the forward code rate is 2 kbps (encoding), and the data rate is 2 kbps to 256 kbps (encoding).

② When the communication distance is 265 km to 3500 km, the antenna beam angle of the two devices is within the range of $(\pm 30^\circ)$. According to the distance, the forward data rate is 2 kbps (encoding), and the return data rate is 16 kbps to 2048 kbps (encoding).

- 2) When the communication distance is 5000 km to 15000 km, the angle range of $(\pm 30^\circ)$ cone angle of the surround UHF-band antenna can ensure the orientation of the rover in any arc. The forward and return channels are coded as convolution $(7, 1/2)$. The data rate is as follows:
- 3) When the communication distance is 5000 km to 9000 km, the antenna beam angle of the rover is within the range of $(\pm 80^\circ)$. According to the distance, the forward data rate is 2 kbps (encoding), and the return data rate is 1 kbps to 2 kbps (encoding). Forward data rate 2 kbps (encoding) up to 12500 km;
- 4) When the communication distance is 5000 km to 15000 km, the antenna beam Angle of the rover is within the range of $(\pm 30^\circ)$. According to the distance, the forward data rate is 2 kbps (encoding), and the return data rate is 1 kbps to 8 kbps (encoding).

3.2 Analysis of X-band Relay Communication Link

X-band relay communication is multiplexed with X-band Mars-earth downlink, and X-band directional antenna is used to transmit return data, corresponding to

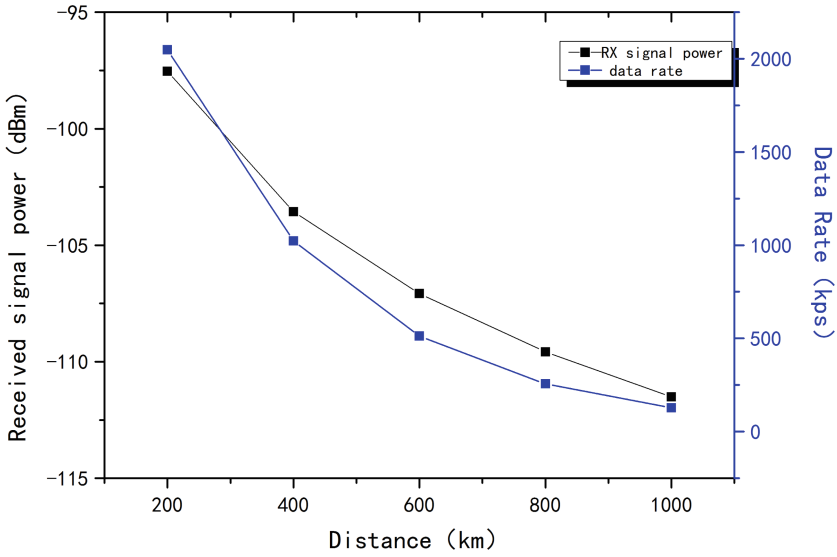


Fig. 3. The Curve of UHF-band Communication Performance.

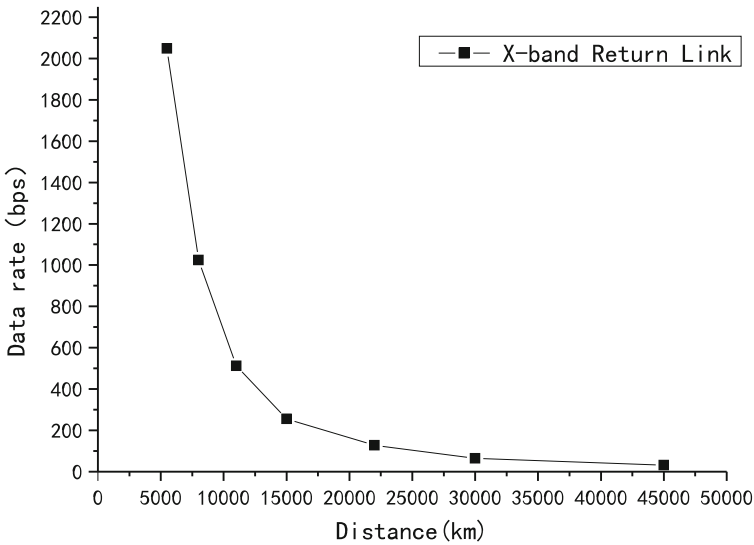


Fig. 4. The Curve of X-band Communication Performance.

orbiter relay receiving antenna, and BPSK modulation is used. The data rate of 32 kbps to 2048 kbps (encoding) is used for the X-band communication during the relay track operation of the orbiter. 15000 km is the maximum communication distance during the relay track operation of the orbiter, and 2048 kbps (encoding) can support the communication of up to 5500 km. Figure 4 shows the relationship

between the communication data rate and the communication distance of X-band relay communication.

4 Analysis of Flight Test Results

At 7:17:58 on May 15, 2021, the lander-rover successfully landed at the pre-selected landing zone in the southern Utopian Plain on Mars. Figure 5 shows the Tianwen-1 Mars probe relay communication system received power during the EDL phase.

At 10:40 on May 22, 2021, the rover safely left the landing platform and reached the Martian surface. By August 16, 2021, the rover had completed 85 apoareon UHF-band relay communication missions, 85 periareon UHF-band relay communication missions, 6 forward UHF-band communication missions, and X-band return communication missions, and transmitted delay telemetry, sensing, exploration data and EDL process data with a total data amount of 16.5 Gb.

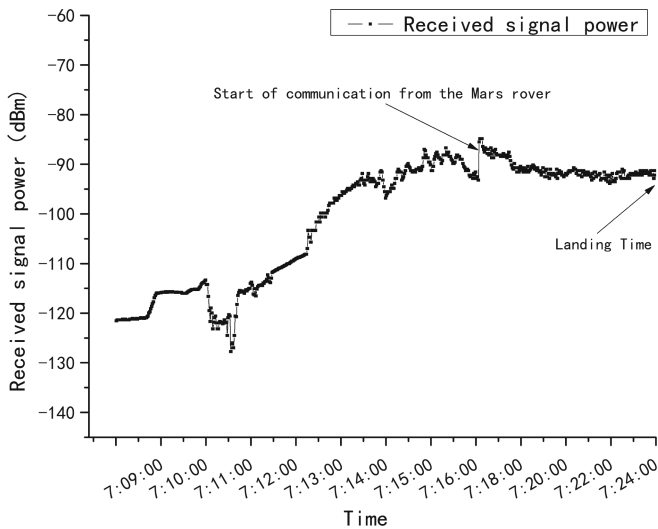


Fig. 5. The curve of received power during EDL phase.

According to the actual operating planning of the rover and orbiter, considering the characteristics of UHF-band antenna and X-band antenna, the relay communication in the periareon arc is carried out at around 14:00 local time of each Martian day in the early and middle exploration phase of the Mars surface, and the communication window duration is about 8 min. In the apoareon arc, one hour of relay communication is selected according to the task arrangement during the Mars night.

In the later phase of the Mars surface exploration, considering the data transmission requirements of large-capacity load data and the path planning strategy of the rover, 6 relay communication missions of forward UHF-band and return X-band were carried out in orbit, with the maximum data amount up to 550 Mb.

From June to July 2021, 60 Mars day periareon relay communication data volumes were selected for statistics. Among them, from July 16 to July 28, due to the adjustment of the communication window time of the orbiter, the transmission of relay data was limited, and the amount of data received by the ground station was about 90 Mb/Sol. The data statistical results are shown in Fig. 6.

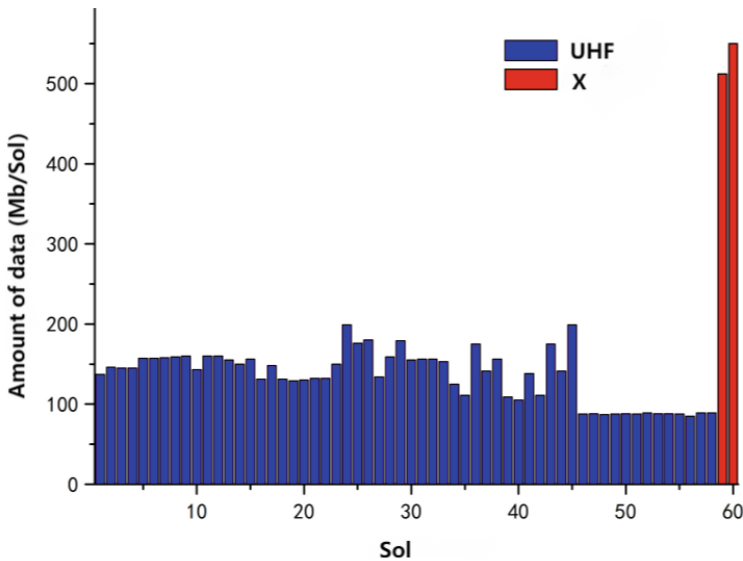


Fig. 6. The data statistical results of Tianwen-1 relay communication.

Through the data statistical analysis of period of Mars surface exploration, and compared with foreign Mars probe trunking communication capabilities, Tianwen-1 Mars probe relay communication system to return to the amount of data transmission in unit time is equal to MRO, and higher than the capacity of Odyssey and Mars Express relay communication link [3]. At the same time, if X-band relay communication link is adopted, the amount of data by the relay communication system of Tianwen-1 Mars probe is about 2.87 times than MRO in unit time. The comparison results of the relay communication systems on Mars at home and abroad are shown in Table 2.

Table 2. Comparison of Relay Communication Capability of Mars Probe at Home and Abroad [4].

Probe Name	Altitude	Average Data Volume (Mb/Sol)	Average Communication Duration (Min/Sol)
Tianwen-1 (UHF)	265 × 15000 km	150	8
Tianwen-1 (X)	265 × 15000 km	500	8
Odyssey	400 km	111	23.4
Mars Express	250 × 10142 km	83	124
MRO	255 × 320 km	327	15

5 Conclusion

The relay communication system of the Tianwen-1 Mars probe is working normally in orbit, successfully completing the engineering objectives of China’s first Mars exploration mission. Mars is verified by in-orbit flight test nodes and relay communication system of the correctness of the scheme design, verify the distances and long time delay under the condition of deep space exploration, the automatic relay communication technology, for our future deep space mission relay communication system for celestial bodies surface probe design and key technology provides the valuable experience of development, it lays a technical foundation for realizing high efficiency and large capacity deep space relay communication.

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