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How Do We Get to Mars? A Comprehensive Analysis of the Technologies, Challenges and Strategies for Crewed Interplanetary Travel

INTRODUCTION

For centuries, Mars has captivated humanity, its mysterious red glow a beacon in our night sky. This fascination has evolved from distant observations to direct exploration, with robots now probing its surface. Our journey from curiosity to exploration is a key chapter in understanding our celestial neighbour. As space exploration enters a new era, the focus shifts from whether we can reach Mars to how and when.

This study explores the myriad challenges and opportunities of a manned mission to Mars, delving into the complexities of space travel and life aboard a spacecraft. It is not just a technical journey but a testament to human ingenuity and our desire to explore. Beyond scientific curiosity, this mission could offer insights into life's origins and a potential refuge for humanity, underscoring the significance of Mars and the irreplaceable nature of our home planet.

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ROCKETS AND SPACECRAFT

Evolution and current state of launch vehicles

In the realm of Mars exploration, various rockets have played crucial roles in deploying rovers and probes. These include the Atlas V, which launched the Mars Reconnaissance Orbiter and the Curiosity rover, and the Delta II, responsible for sending Spirit and Opportunity to the Red Planet. Each of these missions contributed significantly to our understanding of Mars, demonstrating the capabilities and limitations of contemporary launch technology.

Currently, SpaceX's Starship Heavy represents the forefront of launch vehicle development. This spacecraft is designed not just for orbital missions but interplanetary travel, with Mars as a key target. Its development is closely watched by the space community, as it promises to revolutionise space travel (Kramer 2023) with its unprecedented payload capacity and potential for reusability. Starship Heavy's success could dramatically lower the cost of space exploration (Pappalardo 2023) and make ambitious missions like manned Mars expeditions more feasible (Heldmann et al. 2022).

This focus on reusability and efficiency marks a significant shift in launch vehicle design, reflecting the evolving needs and goals of space exploration in the 21st century. Starship Heavy is currently under development. As of the end of the beginning of 2024, it had two test flights, one in April and one in November. Despite a fiery start, both test launches provided SpaceX with essential data for the future.

The emphasis on sustainability, cost-effectiveness and reusability in Starship Heavy's design is a testament to the changing landscape of space travel, where the dream of Mars colonisation is inching closer to reality. We can already see its effect as both China (Beil 2023) and private companies (Rocket Lab 2019) try to shift their focus to reusable rockets and copy SpaceX's approach. The success of Starship Heavy and similar ventures will be pivotal in shaping the future of human space exploration, potentially making Mars not just a distant dream, but a reachable destination.

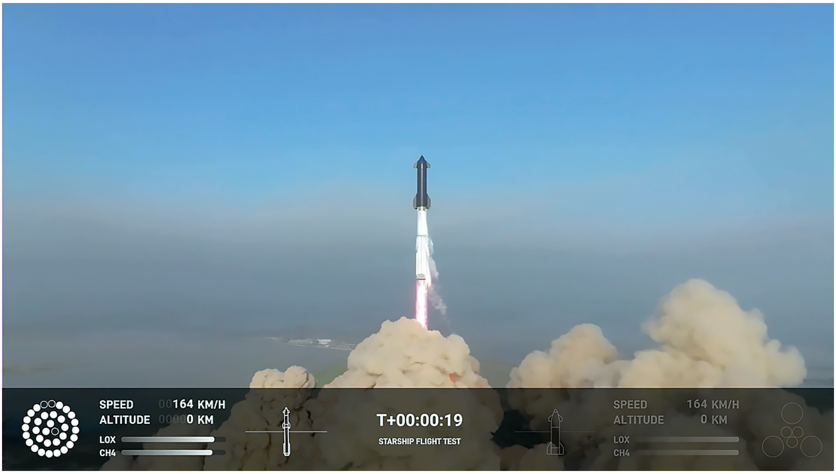

Figure 1
The 1st orbital test launch of SpaceX's Starship Heavy, Boca Chica, TX, USA, 20 April 2023
Source: SpaceX 2023

POSSIBLE ORBITAL PATHS TO AND FROM MARS

As we embark on interplanetary travel, the trajectory we chart from Earth to Mars is not merely a line drawn between two points. It is a carefully orchestrated path governed by the laws of celestial mechanics and the constraints of our technology. The journey to Mars begins with the fundamental question of trajectory. The answer lies not only in the destination but also in the journey itself, where efficiency, safety and the limitations of our spacecraft dictate the course we set.

The Hohmann Transfer Orbit

The *Hohmann Transfer Orbit* (HTO) is a concept that has become the bedrock of space travel. Named after Walter Hohmann, a German engineer who, in 1925, presented it as a fuel-efficient way to travel between two orbits, the HTO is an elliptical path that takes advantage of the orbital mechanics of celestial bodies (Hohmann 1925). Hohmann's revelation was that by timing our launch to coincide with a precise alignment of Earth and Mars, known as an opposition, we could use the least amount of energy to escape Earth's gravity and intercept Mars.

This trajectory involves two key manoeuvres: first, a launch into a parking orbit around Earth, followed by a precisely timed burn that propels the spacecraft into the elliptical transfer orbit, which is designed to be tangential to both Earth's orbit, where the journey begins, and the orbit of Mars, the intended destination. The spacecraft coasts along this path until it reaches the point in its orbit closest to Mars, where another burn adjusts its trajectory to enter an orbit around Mars or land on its surface. The Hohmann Transfer Orbit is a cornerstone in Mars missions, balancing fuel efficiency with practical challenges.

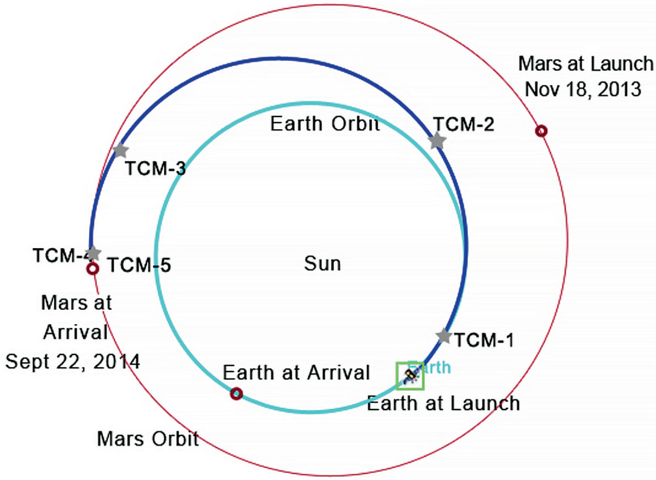

Figure 2
The Hohmann Transfer Orbit demonstrated via NASA's MAVEN Mission
Note: TCM is short for "trajectory correction manoeuvre"
Source: NASA JPL 2014

Its propellant efficiency, crucial for the heavy demands of crewed missions, stems from optimising energy use between Earth and Mars, considering their gravitational forces. This simplicity in design aids in straightforward mission planning and has a proven track record through numerous uncrewed missions, offering reliability and valuable data.

However, HTO's extended travel time, typically around nine months to Mars, raises significant concerns. This duration increases exposure to cosmic radiation and solar particle events, posing health risks to astronauts. The prolonged microgravity environment also impacts psychological and physical health, necessitating comprehensive onboard resources for mitigation. Additionally, HTO's dependence on the specific alignment of Earth and Mars, occurring every 26 months, restricts launch scheduling flexibility.

For human missions, HTO represents a trade-off between minimising fuel consumption and addressing the challenges of extended travel and infrequent launch opportunities. The pursuit of faster transfer orbits and advanced propulsion technologies is driven by the need to overcome these limitations, aiming to make Mars journeys safer and more viable. Fast Transits, as these alternatives are known, seek to significantly shorten travel time, enhancing the feasibility of manned Mars expeditions.

Alternative propulsion technologies

Fast Transits to Mars involve trajectories that are more energy-intensive than the Hohmann Transfer but can cut the travel time to Mars by several months. This reduction is crucial for crewed missions, as it minimises the time astronauts are exposed to cosmic radiation and the detrimental effects of microgravity on the human body. One of the most promising technologies for achieving Fast Transits is the development of advanced propulsion systems.

Nuclear Thermal Propulsion (NTP) (Borowski et al. 2012) can potentially double the efficiency of traditional chemical rockets, allowing for quicker travel times. By heating a propellant like hydrogen with a nuclear reactor, NTP provides a higher specific impulse, which is a measure of propulsion efficiency. As of 2023, no working prototypes were constructed, however, NASA and DARPA have already announced a partnership to create such engines (Hall 2023).

Electric Propulsion, also known as ion or plasma propulsion, is a technology that accelerates ions to create thrust. While it offers a much higher specific impulse than chemical propulsion, its lower thrust levels make it more suitable for cargo missions or as a supplement to other propulsion methods on crewed flights (Dankanich et al. 2010).

Solar Sails uses the pressure of sunlight to propel a spacecraft. Although the acceleration is gradual, over time it can reach high speeds without expending propellant. The concept is new neither to science nor to fiction. In 1865 Jules Verne possibly was the first to describe such a machine in *From the Earth to the Moon*. When talking about the motion of projectiles and planets, he writes "there will someday appear velocities far greater than these, of which light or electricity will probably be the mechanical agent" (Verne 1865). The concept was first tested in 2010 during the successful IKAROS mission after the probe deployed its 20 m-span solar sail (Tsuda et al. 2011).

Free-return trajectory

If our focus is fuel efficiency – and we do not intend to land on Mars – we can also consider free-return trajectories. A free-return trajectory is a path that takes a spacecraft to Mars and back to Earth without requiring significant propulsion manoeuvres for the return journey. This type of trajectory was famously used during the Apollo 13 mission to safely return the crew to Earth (Cass 2005) and is considered a potential safety feature for Mars missions. Although this trajectory might not be ideal for landing crewed missions, for sample returns and resupply missions it should prove to be useful. If we wish to land on Mars using a free-return trajectory, the mission duration would increase significantly as the crew would be forced to wait 550 days until the vehicle circles back to Mars (Landau–Longuski 2004).

The Hohmann Transfer Orbit with a free-return trajectory to Mars would involve launching at a time when the spacecraft can loop around Mars and use its gravity to redirect back to Earth. This "slingshot" effect would allow the spacecraft to return without additional propulsion, providing a built-in abort option should the mission encounter critical issues en route to Mars.

Free-return trajectories, while providing an added safety net for space missions, come with their own set of limitations. A notable drawback is the increased travel time; these trajectories are longer than direct transfers, resulting in a prolonged duration in outer space. Specifically, a mission on a free-return path could spend approximately 530 days continuously in interplanetary space (Donahue–Duggan 2022). Another significant constraint is the limited launch windows. The precise alignment required between Earth and Mars for a free-return trajectory severely limits the number of suitable launch opportunities, with such an opportunity arising only once every 15 years. Additionally, these trajectories offer reduced flexibility; once a mission is committed to a free-return path, there is limited scope to adjust the timeline or alter mission objectives, which can be a critical factor in mission planning and execution.

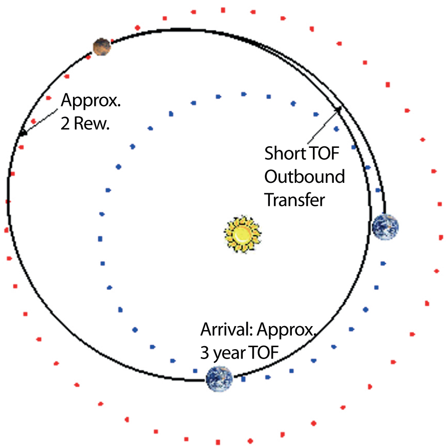

Figure 3
Mars free-return trajectory
Source: Landau – Logunski 2004

In conclusion, while the Hohmann Transfer Orbit remains a viable and efficient route to Mars, the evolution of space travel necessitates the consideration of Fast Transits. These alternatives offer the potential for faster journeys, increased safety, and the pioneering spirit required to push the boundaries of human space exploration.

OBSTACLES OF GETTING TO MARS

Embarking on a voyage to Mars transcends the bounds of human exploration, venturing into realms fraught with challenges both known and unforeseen. This section delves into the myriad obstacles and solutions intrinsic to interplanetary travel, examining the formidable barriers of cosmic radiation, micrometeoroids and the life-sustaining intricacies of advanced life support systems.

The risks and dangers of micrometeoroids

Micrometeoroids, the tiny fragments of rock and metal dispersed throughout our solar system, pose a significant threat to space missions due to their high velocity and ubiquitous presence. Originating from comets, asteroids and the debris left over from the formation of planetary systems, these particles, often no larger than a grain of sand, travel at speeds exceeding tens of kilometres per second (Friichtenicht 1964). This immense velocity endows them with formidable kinetic energy, transforming these seemingly innocuous specks into perilous projectiles in the vacuum of space.

The risk they present is not merely theoretical; numerous spacecraft have borne the brunt of micrometeoroid impacts, most notably, in its two decades, the International Space Station (ISS) has sustained over 1,400 micrometeoroid and orbital debris (MMOD) strikes (Hyde et al. 2019).

Figure 4
MMOD impact on the window of ISS Zvezda Service Module
Source: Riley 2016

Micrometeoroid impacts are inevitable. It is imperative that spacecraft designs incorporate protective measures to ensure that vital life support systems and the astronauts themselves are safeguarded by the craft's outer shell or even by the array of scientific instruments onboard. Given the potential for damage, regular spacewalks may become a routine yet crucial aspect of the mission, allowing astronauts to inspect and address any impairments caused by these cosmic assailants.

Leveraging the ISS's MMOD shielding techniques, future crewed Mars missions could adopt similar protective measures. Key among these is the "Stuffed" Whipple (SW) shield, an advanced version of the standard Whipple shield, comprising an outer aluminium bumper, a non-metallic intermediate layer and an inner rear wall. This design is particularly effective in areas prone to higher MMOD impacts, such as a spacecraft's forward and lateral sections. For

Mars missions, optimising the standoff distance between these layers, typically between 10 and 30 cm on the ISS, will be crucial in balancing protection with spacecraft design constraints and launch vehicle capacities (Christiansen et al. 2009).

Radiation in interplanetary space

Space radiation presents a formidable challenge for Mars-bound astronauts. Unlike the relative safety provided by Earth's magnetic field and atmosphere, space offers no such protection, exposing travellers to a relentless barrage of cosmic rays and solar radiation.

Cosmic rays, originating from distant supernovae and other astrophysical phenomena (Drury 2012), consist of high-energy particles that can penetrate deep into both spacecraft and human tissue. Solar radiation, emanating from our own Sun, also contains these charged particles (Parker 1965) and includes a spectrum of harmful emissions.

These radiations not only pose a risk to the physical health of astronauts, through increased cancer risk and potential damage to the central nervous system (Simonsen et al. 2020) but also threaten the integrity of spacecraft electronics and materials.

Addressing the risks posed by space radiation is a critical component of mission planning for Mars. The development of effective shielding is a primary focus, with researchers exploring materials and technologies that can absorb or deflect these high-energy particles. Innovations such as water-based shielding, where water tanks or supplies double as a protective barrier (Adamo–Logan 2016), new composite materials or even mini-magnetospheres (Bamford et al. 2014) are at the forefront of this research. Beyond physical barriers, mission planners also strategise to minimise exposure time, particularly during periods of intense solar activity (Simonsen–Nealy 1991).

Life support and sustenance

In the context of a Mars mission, life support and sustenance are critical components that ensure the survival and well-being of astronauts (Wieland 1994). The life support system on a spacecraft bound for Mars must be robust and largely self-sustaining, capable of recycling air, water and possibly even waste.

Advanced systems for air revitalisation and water recovery are essential. These systems must efficiently recycle carbon dioxide back into oxygen and purify water from various sources, including humidity from the air and astronauts' waste. The technology used on the ISS, such as the Environmental Control and Life Support System (ECLSS) (Brown–Tobias 2020), provides a foundation, but these systems will need enhancements for the longer duration and greater autonomy required for Mars missions.

Sustenance for Mars missions poses unique challenges due to the extended duration and limited cargo capacity. Traditional methods of storing food for space missions, which rely on pre-packaged meals, may not be viable for the longer Mars missions (Obrist et al. 2019). Instead, research is being directed towards more sustainable solutions, such as growing food in space (Salisbury 1999). Hydroponic and aeroponic systems are being explored for this purpose (Oluwafemi 2018). These systems must be energy-efficient, require minimal resources, and be capable of growing a variety of nutritious foods to meet the dietary needs of astronauts.

Future Mars missions may also see the implementation of more advanced life support technologies. Concepts like bioregenerative life support systems (Fu et al. 2016), which use biological processes to recycle waste and produce food and oxygen, are being studied. These systems could potentially create a more Earth-like environment, aiding not just in physical health but also in psychological well-being.

LANDING ON MARS

Entry, descent and landing

The Entry, Descent and Landing (EDL) phase of a Mars mission is fraught with challenges, due to delay in communication and the thin Martian atmosphere. This atmosphere is thick enough to generate significant heat during entry, necessitating robust heat shields, yet too thin for conventional parachutes to slow a spacecraft sufficiently for a safe landing (Huang 2020). This paradox has led to the development of innovative EDL technologies.

Aerobraking, a technique where the spacecraft uses the Martian atmosphere to slow down, plays a crucial role (Luo–Topputo 2021). The spacecraft's heat shield must withstand extreme temperatures during this high-speed entry (Edquist et al. 2014). Following aerobraking, parachute deployment is the next critical step. However, given the thin atmosphere of Mars, parachutes alone cannot decelerate the spacecraft to safe landing speeds. This limitation has spurred the development of retro propulsion techniques (Korzun et al. 2008), where rockets are fired in the opposite direction of travel to further reduce speed.

The Sky Crane manoeuvre, successfully employed by NASA's Curiosity (Way et al. 2007) and Perseverance (Maki et al. 2020) rovers, exemplifies the innovative solutions to these challenges. In this manoeuvre, a rocket-powered descent stage lowers the rover on cables to the surface, allowing for a controlled and precise landing even in rough terrain. This technique, while complex, has proven effective in safely delivering payloads to specific Martian locations.

The advent of reusable rockets, such as SpaceX's Starship, represents a significant shift in how we approach crewed missions to Mars. Unlike previous missions that relied on sky cranes for precision landing, the Starship envisions a direct, rocket-powered descent onto the Martian surface. SpaceX's participation in NASA's Artemis program, which aims to return humans to the Moon, will serve as a vital testing ground for the capabilities of Starship.

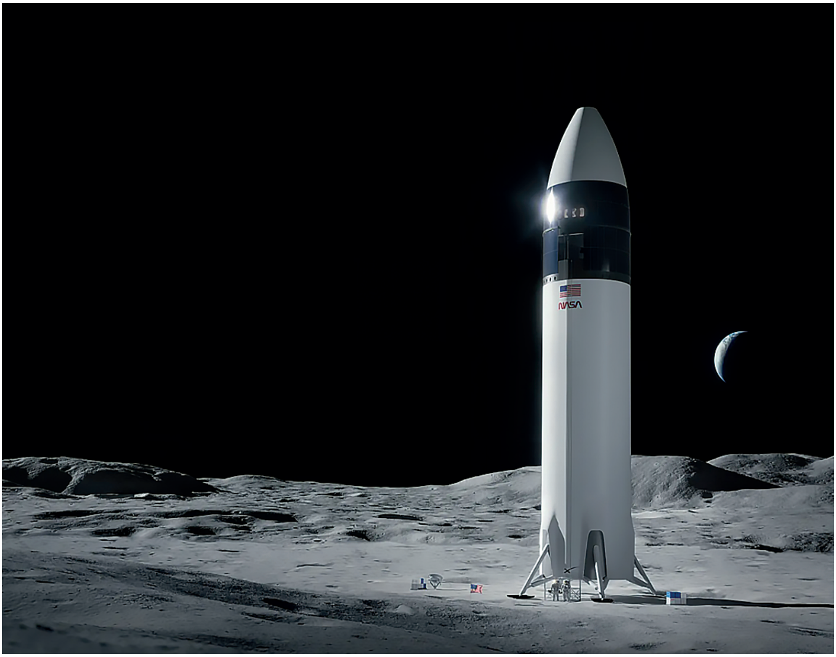

Figure 5
Artist's concept of SpaceX's Human Landing System on the surface of the Moon
Source: NASA 2022

In 2021 NASA and SpaceX signed a contract (NASA 2021) to develop and manufacture the Starship Human Landing System (HLS) and conduct a test flight and a crewed mission. The lunar missions will provide essential data on the performance of the Starship in extraterrestrial landing and launch scenarios, directly informing its adaptation for Mars missions.

The concept of precision landing by rocket propulsion was tested on 19 January 2024 by the Japan Aerospace Exploration Agency (JAXA). Their Smart Lander for Investigating Moon (SLIM) lander touched the Lunar surface 55 m East of the targeted landing site proving the capability of such technology (JAXA 2024).

Suitable landing sites

Selecting suitable landing sites on Mars is a complex process that involves balancing scientific interests with practical considerations. Key factors include terrain analysis, availability of water ice, access to solar energy, dust storm patterns and the site's overall accessibility.

Terrain analysis is crucial for ensuring a safe landing and operation of the mission. Sites must be flat and at a low altitude to facilitate a safe landing and provide a stable base for operations. The presence of water ice is a significant factor, as it not only offers potential resources for sustaining human life but also for fuel production.

One such landing area, the Vernal crater area in Arabia Terra, presents a compelling case as a landing site for future human exploration (Pajola et al. 2022). Its geological richness, evidenced by the presence of ancient hot springs, aeolian ridges and a diverse bedrock stratigraphy, offers significant exobiological interest. The site's high water equivalent hydrogen content (Wilson et al. 2018) suggests abundant in-situ resources like water ice and hydrated minerals (Stamenković 2019), crucial for sustaining human presence and potential in-situ resource utilisation. Additionally, its equatorial location ensures optimal surface temperatures and solar flux, making it not only scientifically intriguing but also practically viable for long-term human exploration.

Previous landing sites, such as those of InSight (Golombek et al. 2020) and Viking missions, offer valuable insights into Martian conditions and potential resources. These sites have been thoroughly studied, providing a wealth of data that can inform future missions.

Pre-deployment of supplies

In Mars exploration, the debate between pre-deploying assets versus carrying everything on the mission is pivotal. Pre-deploying habitats and supplies can reduce risk and cargo requirements for crewed missions, allowing for more scientific equipment or redundancy systems. This kind of mission planning will be tested in NASA's Artemis program on the lunar surface (Smith et al. 2020).

However, this approach relies heavily on successful prior missions and in-situ resource utilisation for long-term sustainability. Conversely, carrying all necessary supplies and equipment offers greater mission flexibility and immediate self-sufficiency but demands significantly higher cargo capacity and advanced logistics planning. Balancing these approaches is key to ensuring the success and safety of Mars missions.

COMMUNICATION AND CONNECTION WITH EARTH

The challenges of time delay

The communication between Earth and Mars is subject to significant time delays, varying from a few minutes to over twenty minutes one-way, depending on the relative positions of the two planets. This delay poses unique challenges, especially when compared to lunar missions where the delay is negligible. For instance, the Apollo missions to the Moon benefited from near real-time communication, allowing for immediate ground support in decision-making. In contrast, Mars missions, such as the autonomous landings of rovers, must rely heavily on pre-programmed systems and autonomy in decision-making due to the delay (Wong et al. 2002).

This time delay was most dramatically illustrated during the "seven minutes of terror" (NASA Jet Propulsion Laboratory 2012) – the time it takes for a probe to enter the Martian atmosphere and land on the surface, all occurring without real-time intervention from Earth. During this period, the spacecraft must autonomously execute a series of complex manoeuvres, as any command from Earth would arrive too late to be of use.

To address these challenges, missions to Mars employ various time delay protocols and asynchronous communication strategies (Bhasin et al. 2001). These include extensive pre-mission programming, robust autonomous systems capable of making critical decisions independently (Harris et al. 2019), and the use of 'if–then' logic to handle different scenarios that the spacecraft might encounter. This approach ensures that despite the communication lag, missions can proceed safely and effectively, albeit with a greater reliance on the spacecraft's onboard systems and less on real-time inputs from mission control.

Current communication technologies with Martian probes

Current communication with Mars probes relies on NASA's Deep Space Network (DSN) (Rogstad et al. 2005), a global array of large antennas providing the vital link for data transmission to and from distant spacecraft. Mars rovers, such as Curiosity and Perseverance, primarily communicate with Earth through orbiters, acting as relays. This system enhances the data rates achievable, compared to direct rover-to-Earth communication, which is limited by the rovers' smaller antennas and lower power.

The DSN supports high-bandwidth communication, essential for transmitting large volumes of scientific data, including high-resolution images and detailed instrument readings. However, the data rates are still relatively modest, constrained by the vast distance between Mars and Earth and the current limitations of radio-frequency technology.

The applicability of these communication technologies to crewed missions is a subject of ongoing research and development (Cesarone et al. 2007). While the existing infrastructure has served robotic missions effectively, the demands of a crewed mission, including higher data rates for more complex operations and the need for more consistent and reliable communication, will necessitate enhancements to the current system. This could involve the deployment of more powerful orbiters around Mars or the development of new communication technologies to ensure a robust and continuous link with a crewed spacecraft.

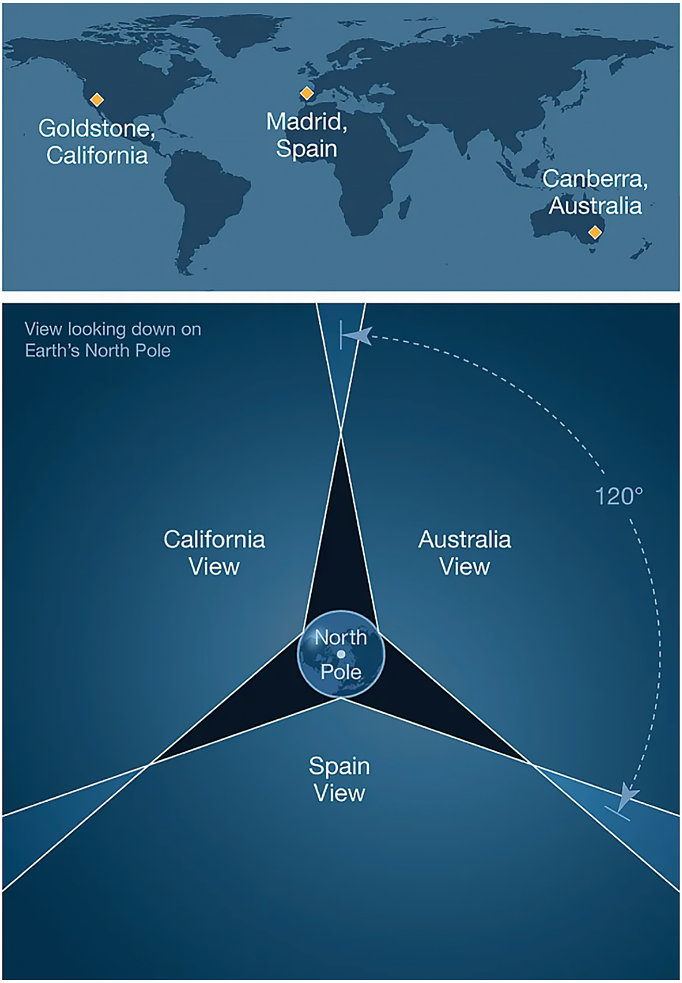

Figure 6
NASA's Deep Space Network consists of three strategically placed radio arrays to minimise blind spots
Source: NASA 2023a

Satellites and continuous communication

Continuous communication with Mars is challenged by the orbital dynamics of Earth and Mars, leading to periods when direct communication is almost impossible due to solar conjunction (Morabito–Hastrup 2002) when the Sun lies directly between the two planets. This event occurs approximately every 26 months and can last for about two to three weeks, during which communication with Mars missions is severely limited or entirely paused to avoid interference from the Sun's corona (Pätzold et al. 2012).

To address this, a network of orbiters placed into the L4 and L5 points of the Sun–Mars system equipped with advanced communication technology could provide continuous data relay and coverage (Breidenthal et al. 2018), ensuring a stable communication link even during solar conjunction. These orbiters would need to be strategically positioned to maintain a line of sight with both the Martian surface and Earth, overcoming the bandwidth limitations and logistical challenges posed by the vast distance.

For emergency communication protocols during solar conjunction, alternative strategies such as pre-programmed autonomous operations for Mars-based assets and the use of redundant communication systems are essential. These measures would ensure that missions can continue to operate safely and effectively, even when direct communication with Earth is not possible (NASA 2023b). The implementation of such a comprehensive communication infrastructure would be a significant step towards ensuring the safety and success of future crewed missions to Mars.

CONCLUSIONS

The endeavour to send humans to Mars represents a paradigm shift in our cosmic aspirations, encompassing a broad spectrum of technological, physiological and logistical challenges. This study has systematically dissected the multifarious elements that underpin such a mission, elucidating the nuanced interplay between advanced propulsion systems, life support technologies and interplanetary communication strategies.

Foremost in this venture is the evolution of launch vehicles, exemplified by SpaceX's Starship Heavy or China's Long March 9. This innovation in rocketry not only signifies a leap towards more sustainable space travel but also redefines our approach to interplanetary missions, positioning Mars as an attainable destination. The shift towards reusability and cost-effectiveness in these vehicles reflects a broader transformation in space exploration philosophy, aligning with the imperatives of long-term sustainability and accessibility.

Trajectory planning to Mars highlights a critical balance between efficiency and safety. While traditional paths like the Hohmann Transfer Orbit offer fuel efficiency, the exploration of Fast Transit trajectories – enabled by advancements in propulsion technologies such as Nuclear Thermal Propulsion and Electric Propulsion – opens avenues for reduced travel times and enhanced crew safety.

Addressing the hazards of micrometeoroids and cosmic radiation involves a confluence of engineering prowess and innovative shielding solutions. These protective measures not only safeguard spacecraft integrity but also ensure the well-being of astronauts, underlining the mission's human-centric focus. Similarly, the development of sophisticated life support systems, encompassing air revitalisation and water recovery, demonstrates a commitment to creating sustainable and habitable environments in space.

The complexity of Mars landings necessitates a fusion of aerobraking, retropropulsion and precision landing technologies, underscoring the intricate engineering required for successful extraterrestrial touchdowns. Moreover, the strategic selection of landing sites integrates scientific objectives with practical considerations, highlighting the meticulous planning inherent in these missions.

Finally, the study emphasises the imperative of robust communication systems to overcome the challenges posed by interplanetary time delays. The advancement of communication technologies and strategies is pivotal in ensuring continuous and reliable contact with Earth, an essential aspect of mission safety and success.

In conclusion, this study affirms that crewed Mars missions are not merely feats of engineering and science but are emblematic of humanity's enduring quest for knowledge and exploration. As we edge closer to realising this monumental goal, the journey to Mars stands as a testament to human ingenuity, resilience and the unyielding spirit of discovery.

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