Investigating the Impact of Communication Delay on Mission Control as an Effective Team Member with the Crew

by

Sideena Grace

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Authored by: Sideena Grace
Department of Aeronautics and Astronautics
May 23, 2023

Certified by: Wesley L. Harris
Professor, Aeronautics and Astronautics
Thesis Supervisor

Accepted by: Jonathan P. How
R.C. Maclaurin Professor of Aeronautics and
Astronautics, Graduate Program Committee

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Abstract

The National Aeronautics and Space Administration (NASA) aims to send humans to Mars in the coming decade. However, the significant communication delay of up to 22 minutes one way poses challenges for Mission Control (MC) in fulfilling its role as an effective team member with the crew, potentially jeopardizing mission safety and success. Existing research on communication delay has primarily focused on the crew, neglecting the impact on MC. This study addresses this gap by investigating the impact of communication delay on MC's role as a team member and proposes a protocol to improve communication between MC and the crew. To analyze the impact of communication delay, data from high-fidelity analog studies and the International Space Station (ISS) were examined. These studies covered scenarios with delays ranging from seconds to 20 minutes, communication blackouts, and mission durations up to 520 days. Tasks of varying complexity were evaluated to assess MC's ability to support the crew. Additionally, existing protocols were evaluated using subjective ratings and compliance analysis. The analysis indicated that communication delay significantly impairs MC's effectiveness as a team member, evidenced by common challenges identified in the studies. These challenges include difficulty for MC in understanding the crew's needs and maintaining situational awareness due to communication breakdowns. As a result, MC faced challenges in providing consistent and accurate support to the crew. The delayed recovery from these challenges led to reduced reliance on MC by the crew, as their role was not always seen as the most efficient option for seeking support. In response, a new protocol focusing on tone was developed to establish effective and respectful communication between MC and the crew, to mitigate the effects of these identified challenges. Furthermore, two key recommendations emerge from the analysis: ensuring time delay consistency and standardizing communication delay implementation. These recommendations aim to optimize the effectiveness of protocols and provide a better understanding of their impact in addressing communication delay. Understanding the impact of communication delay on both MC and the crew is vital for developing protocols that enhance effective communication and teamwork during the mission. These findings contribute

to optimizing protocols for future studies and preparing for the Mars mission.

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This remarkable journey may have been undertaken by me, but it would not have been accomplished without the grace of God and the unwavering support and guidance of those who have supported me every step of the way.

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Nomenclature

Acronyms

CSA - Canadian Space Agency

HERA - Human Exploration Research Analog

Hi-SEAS - Hawaii Space Exploration Analog and Simulation

ISS - International Space Station

JAXA - Japan Aerospace Exploration Agency

MCC - Mission Control Center

MC - Mission Control

MTS - Multiteam Systems

NASA - National Aeronautics and Space Administration

NEEMO - NASA Extreme Environment Mission Operations

SIRIUS - Scientific International Research In a Unique terrestrial Station

Chapter 1

Introduction

NASA's ambitious vision to send humans on a multi-year mission to Mars in the upcoming decade marks an unprecedented milestone in space exploration [17]. With a distance of approximately 140 million miles from Earth, this mission presents unique challenges that surpass any previous endeavors, including extreme isolation, confinement, prolonged duration, and increased distance from Earth [18]. However, achieving success in this mission demands not only the advancement of cutting-edge technology, but also the critical involvement of MC as an integral team member with the crew [19].

MC holds a vital role in spaceflight as they bear the responsibility of monitoring mission operations and ensuring crew safety. They actively participate in decision-making processes and are pivotal in resolving any mission-related issues that may arise [20]. Despite the indispensability of MC as a key team member, research examining the challenges directly impacting their role has been largely neglected. One prominent challenge that MC will face is communication delay, which can reach up to 22 minutes one way [21]. This significant time delay necessitates adaptations in MC operations from the current real-time communication and decision-making processes employed on the ISS, as the crew will be autonomous, leading to their heightened involvement in decision-making processes. Addressing the challenges posed by communication delay will be crucial for establishing effective communication between MC and the crew, which is vital for ensuring seamless teamwork and mission success [21].

In the background, I will provide information on the current benefits and challenges of MC's role as a team member and then I will discuss the problem statement, specific aims, and hypotheses for this thesis.

1.1 Background

MC has long been recognized as an essential component in ensuring crew safety and mission success [20, 22]. In the early days of the spaceflight program, MC operations were distributed across various locations due to technological limitations, requiring launch operations, telemetry management, and ground communication stations to be stationed at separate remote sites. However, technological advancements during the Gemini project allowed MC to centralize its operations in a single location at NASA's Mission Control Center (MCC) in Houston, Texas [20]. Over time, MC operations have continued to evolve and adapt to the challenges posed by each new mission, leveraging the latest technology to enhance their capabilities.

(a) **(b)**

Figure 1-1: (a) Overall view of the NASA Apollo Mission Control Room located at Johnson Space Center in Houston, Texas [1],(b) and the current view from Mission Control Center at NASA's Johnson Space Center in Houston, Texas (Photo credits: NASA) [2].

MC functions through a hierarchical approach, relying on a large team of experts who collaborate to ensure crew safety and mission success [20]. The MCC serves as the primary communication hub for the crew and holds significant decision-making

authority for each mission [20, 23, 16]. Protocols developed by experts guide MC's actions, outlining standard procedures, communication protocols, and contingency plans for emergency situations and critical systems [24]. These protocols facilitate efficient and effective operations while mitigating potential risks. As space exploration progresses, these protocols for decision-making, communication, and contingency actions continually evolve and improve. Notably, different MCCs have developed their own distinct protocols, reflecting the diverse approaches taken by various space agencies. For example, due to the collaborative nature of the ISS, the management of its crews and systems involves multiple MCCs from various space agencies. While all MCCs play a crucial role in spaceflight operations, this thesis specifically focuses on NASA's MC.

NASA's MCC consists of two distinct areas: the front room and the back room [25, 26]. The front room comprises flight directors, flight engineers, and specialists from various fields who are responsible for supporting the mission's objectives. They manage ground-based information flow, troubleshoot computer networks, oversee shared computer displays, and monitor and troubleshoot ground-space data exchange [16]. The back room consists of a larger group of experts who provide support to the front room. This division into front and back rooms prevents overcrowding and enables a more efficient and streamlined communication process with the crew. In addition to their technical duties, MC also plays a vital role in providing emotional and social support to the crew. They are responsible for ensuring the astronauts' physical and mental well-being, mitigating the stressors of spaceflight, and optimizing their performance in achieving mission objectives [20, 23]. This section will explore the benefits and challenges of NASA's MC as a team member with the crew, shedding light on their critical role in human spaceflight missions.

1.1.1 Benefits of Mission Control Role as a Team Member:

MC serves as the primary communication hub for astronauts and plays a critical role in providing both technical guidance and essential emotional and social support

during spaceflight missions. While other support systems exist, such as psychological support and communication with family and friends, MC's involvement is vital in ensuring the well-being of the crew. The isolation and confinement experienced during space missions can give rise to psychological disorders, including depression and anxiety, as well as interpersonal problems such as communication breakdowns and conflicts [19]. These issues have the potential to jeopardize crew safety and compromise mission success, and are anticipated to increase in frequency in longer and more challenging missions, as stated by NASA [27].

To ensure effective communication and crew well-being, protocols have been established that assign MC with the responsibility of supporting the crew and addressing any concerns or issues that may arise. These protocols include conducting debriefing sessions after critical events, providing opportunities for crew members to discuss psychosocial issues and foster stronger relationships within the crew [28]. Additionally, MC undergoes training to offer support and advice, enabling them to assist the crew in working through these issues and ensuring their effective resolution.

In addition to emotional support, MC plays a crucial social role in maintaining the well-being of the crew. Astronauts are disconnected from the rest of the world for extended periods, which can lead to feelings of loneliness and isolation [19]. MC's constant presence serves as a vital connection to Earth, promoting crew morale and motivation, particularly during longer and more challenging missions. The emotional and social support provided by MC serves to prevent and address psychosocial problems, while fostering a sense of connection to Earth. Such support enhances the crew's ability to perform their mission safely and successfully.

1.1.2 Challenges of Mission Control Role as a Team Member:

Although the role of MC is crucial for ensuring the safety of the crew, it has not been without challenges and negative experiences for the crew [27]. The protocols

provided to the MC can create significant challenges for the crew, especially during prolonged and complex space missions that involve increased workload and stressors. These challenges have highlighted the negative impact of MC's operation style on the crew [29].

According to Collins (1985), the Skylab mission presented several challenges for the crew, including heightened isolation and confinement due to the duration, which led to significant psychological strain. Due to this,The astronauts experienced feelings of loneliness, irritability, disconnection, alienation, and frustration. Additionally, the crew felt heavily micromanaged by MC in conducting repairs and scientific experiments, leading to disagreements. Despite these challenges, the crew worked with MC to address the issues and improve their effectiveness and performance to avoid mission failure.

Currently, the role of MC for the ISS remains largely the same, with astronauts having limited autonomy and decision-making power, despite the challenges faced by crews in past missions [30]. MC plays a significant role in the decision-making process, from scheduling to task instructions, which restricts the crew's autonomy and decision-making abilities. A study by McIntosh et al. (2016) involving interviews with former astronauts, operational support personnel, and MC personnel revealed a perceived rift between MC and crew members. MC's operation style was described as micromanaging and militaristic, leading to an "us versus them" mentality, which may be attributed to the lack of joint planning for mission operations. The interviewees believed that a more mutualistic approach to mission planning, with deep involvement of the crew in the decision-making process alongside MC, is necessary. While no crew member has defied communication protocols or challenged the decision-making process that could lead to life-threatening outcomes, one reason crew members refrain from doing so is the consequences of challenging the current operation. However, it is crucial to acknowledge that without modifications to the current operations to provide a more balanced dynamic between MC and the crew, including greater autonomy

and decision-making power for the crew, these issues will continue to persist.

MC's role will be significantly affected by communication delay, challenging their effectiveness as a team member with the crew. Therefore, to effectively fulfill their role as a team member, MC needs to evolve by fostering greater coordination and collaboration with the crew. Such efforts will be crucial for successful long-duration missions to Mars. [23].

1.2 Problem Statement:

As NASA prepares for the upcoming Mars mission, it is crucial to understand the impact of communication delay and develop protocols to address the associated challenges. Studies conducted in high fidelity analogs and the International Space Station (ISS) are valuable tools for simulating the unique challenges that astronauts will face, including isolation and confinement, and communication delay, thereby aiding in mission preparation. Analog studies offer cost-effective simulations of spaceflight effects, while the ISS provides conditions that closely resemble those encountered during the actual mission. By leveraging these studies, we can gain valuable insights into the conditions and challenges that astronauts will face on the Mars mission, facilitating better preparation. However, previous research has largely overlooked the impact of communication delays on the Mission Control (MC) despite its critical role in supporting the crew during space missions. This knowledge gap is concerning, as any negative effects on MC can have far-reaching consequences for the entire mission. To mitigate these challenges, it is imperative to develop protocols; however, without a comprehensive understanding of the impact of communication delays on MC, these protocols may not effectively support communication between MC and the crew. Failing to address communication delays can result in minor performance and well-being impacts on the crew or even catastrophic outcomes like mission failure. Therefore, conducting focused research on the impact of communication delays

on MC and proposing a new protocol, as well as improvements to existing ones, is imperative to effectively address these challenges.

1.2.1 Specific Aims:

The aims of this thesis are as follows:

- Identify the impact of communication delay challenges on the role of MC as an effective team member with the crew.
- Propose a new protocol and provide recommendations to enhance current protocols in addressing communication delay challenges.

1.2.2 Hypotheses:

The hypotheses of this thesis are as follows:

- Communication delay will have a significant impact on MC's current role as an effective team member with the crew.
- Current research on communication delay protocols in studies lacks consistent implementation and standardization, necessitating protocol improvements for more effective communication in future studies.

1.3 Contribution:

The primary contribution of this thesis can be divided into two main aspects. Firstly, it seeks to enhance our understanding of how communication delay impacts MC's effectiveness as a team member with the crew, thereby shedding light on their critical role in ensuring mission success. Secondly, this study provides a new protocol and recommendations for enhancing existing protocols to improve effective communication between MC and the crew during communication delay.

1.4 Thesis Outline:

Chapter 1: Introduction

This chapter provides an introduction to the thesis by presenting the background, stating the problem, outlining the specific aims, hypotheses, and contribution. It establishes the foundation for the subsequent chapters and sets the context for the research.

Chapter 2: Literature Review

In this chapter, a comprehensive review of the relevant literature is presented. It covers topics such as multiteam systems (MTS), communication methods, communication delay challenges, protocols, and current research limitations. The chapter establishes the theoretical framework and contextual understanding necessary for the study.

Chapter 3: Methods

This chapter delves into the research methodology employed in the study, providing a detailed explanation of how the research was conducted. It outlines the specific data analysis techniques used, the research questions that guided the study, and the ethical considerations taken into account during the research process. Additionally, the chapter acknowledges and discusses the limitations inherent in the chosen methodology.

Chapter 4: Impact of Communication Delay on MC's Role

This chapter focuses on the core findings of the study. It examines how communication delay challenges specifically impact MC's role as an effective team member. The chapter presents a thorough analysis of the results, drawing meaningful insights from the data collected.

Chapter 5: Proposed Protocol and Recommendations

In this chapter, a new protocol is introduced, accompanied by recommendations aimed at improving the effectiveness of existing protocols when dealing with communication delay challenges. The proposed protocol offers a novel approach to addressing the impact of communication delays on mission control and the crew, while the recommendations provide insights into optimizing the existing protocols

Chapter 6: Discussion and Conclusion

The final chapter synthesizes the key findings from the study and offers a comprehensive discussion. It highlights the significance of the research, draws conclusions, and reflects on the implications of the results. Additionally, the chapter provides recommendations for future research beyond the scope of this thesis, emphasizing avenues for further exploration in the field.

Chapter 2

Literature Review

The literature review will focus primarily on the impact of communication delay in analog and ISS studies. The review is divided into several sections, including MTSs, communication methods, communication delay challenges, communication delay protocols, and current research limitations. The MTS section covers the fundamental concept of MTS. The second section investigates the challenges of communication delay found in analog and ISS studies. The third section discusses current protocols for addressing communication delay challenges. The final section discusses remaining limitations in research.

2.1 Multiteam Systems

MTS are two or more teams that collaborate as a single entity to achieve their shared goals and have become increasingly popular in many fields [31]. Several entities, including space agencies, aviation industry, medical institutions, military organizations, and first responders use MTSs. These systems are crucial in accomplishing multifaceted tasks in high pressure and hazardous environments where suboptimal performance can have serious consequences. [32].These systems require the coordination and integration of diverse skills and expertise distributed across individual teams, enabling them to overcome intricate challenges in innovative ways.

The growing number of studies on MTS in various settings has provided a wealth of empirical data, going beyond the initial theoretical assumptions, and enabling us to expand our knowledge in an evidence-based way [32]. However, MTS in the field of spaceflight is currently not as extensively studied as MTS in other fields. Further research is needed to better understand how MTS can work together more effectively to ensure safe and successful space missions [33, 34]. The ISS provides an example of an MTS where MC and the crew must work together as a team [35]. Given the increasingly complex challenges faced in spaceflight conditions, it is becoming increasingly challenging to identify the factors that contribute to effective teamwork.

To optimize the efficacy of teamwork within MTSs, effective communication plays a pivotal role. It is essential for aligning all teams towards a shared goal, synchronizing their efforts, and minimizing conflicts and failures [33, 34]. Achieving this requires the implementation of various strategies, including establishing shared mental models, well-defined decision-making processes, and clear communication protocols. These measures foster effective information exchange, facilitate understanding among team members, and enable cohesive coordination to navigate the complexities of MTS operations.

2.2 Communication Methods

Effective communication between MC and the crew is crucial for ensuring mission safety and success. Given the significant distance between them, various types of communication methods are utilized, including face-to-face, remote synchronous communication, and remote asynchronous communication. Each of these methods presents its own advantages and challenges [36].

2.2.1 Face-to-face

Face-to-face communication, whether in person or in a virtual setting where individuals can see each other, is widely recognized as one of the most efficient types of

communication. Its numerous advantages, such as enabling clear communication and facilitating situational awareness are invaluable [37]. For space missions, face-to-face communication between MC and the crew on the ISS is facilitated through video communication, allowing them to have virtual face-to-face interactions [16]. This type of communication becomes especially crucial in situations where phenomena cannot be easily described or understood through audio or written messages alone [37]. For instance, face-to-face interaction allows for the conveyance of emotions, attitudes, and intentions through body language and facial expressions, which can minimize misunderstandings and enhance the clarity of intended messages.

Additionally, face-to-face communication allows for smoother and uninterrupted interaction. It enables individuals to take turns speaking and responding to each other without interruptions or talking over one another [38, 39]. This promotes a more orderly and structured exchange of information, reducing the risk of messages becoming disorganized or out of sequence [38]. Visual cues and body language play a crucial role in indicating when someone has finished speaking or when it is appropriate to interject, helping to maintain focus and productivity in the conversation [39].

Furthermore, face-to-face communication fosters a greater level of understanding, which is crucial for task completion. Through visual and auditory channels, team members can observe each other's reactions and responses, providing valuable feedback on the clarity and effectiveness of the message conveyed. This shared visual field enhances comprehension and cooperation among team members, facilitating mutual understanding and collaborative problem-solving [39]. In situations involving unexpected emergencies or critical medical concerns that require prompt decision-making, the immediacy and richness of face-to-face interaction become particularly valuable [**?**]. Moreover, facial expressions and gestures serve as non-verbal cues to direct attention and gauge understanding, leading to efficient and effective communication.

In addition to these advantages, face-to-face communication offers a unique op-

portunity for personal connection among team members. The ability to see facial expressions and body language provides valuable insight into their level of engagement and investment in the task at hand [38, 39]. This deeper level of connection fosters trust and empathy, cultivating a stronger sense of shared purpose and commitment among team members. By understanding non-verbal cues, team members can collaborate more effectively, building mutual respect and fostering a deeper level of understanding.

Overall, face-to-face communication stands out as the most powerful method, offering a combination of enhanced message delivery, efficient coordination, and the ability to foster stronger interpersonal connections and mutual understanding among team members. These factors collectively contribute to the success and effectiveness of communication within teams.

2.2.2 Remote Synchronous Communication

Remote synchronous communication refers to immediate audio and text communication between two remote people or teams who are located remotely [36]. Although it lacks a visual component, it provides real-time communication, which is highly valuable. This form of communication enables instant exchange of information and allows for timely decision-making and coordination, even in situations where face-to-face interaction is not feasible.

Audio communication offers the advantage of conveying the nuances of face-to-face interactions, such as tone, inflection, and emotion, which are crucial for clarifying the intended message [36]. For instance, vocal inflection can convey anxiety or urgency, providing additional context even if the words themselves do not explicitly express these emotions. On the other hand, text communication provides the benefit of message review and permanent documentation, allowing for the recall of past conversations and decisions, thereby reducing cognitive load and serving as a reference for future actions [36].

However, remote synchronous communication also presents challenges. The most significant challenge is the absence of visual cues, which are crucial for comprehending the message due to the role played by facial expressions and body language in communication [36]. This necessitates the need for more explicit communication and the utilization of additional cues, such as tone of voice or text formatting, to ensure accurate interpretation and understanding, particularly when conveying agreements or disagreements. Text communication, in particular, can be challenging as it lacks the ability to convey tone, potentially leading to misunderstandings or misinterpretations [36]. Furthermore, text communication exchange often take longer as they require more detailed information to ensure a comprehensive understanding, resulting in longer response times [39]. In certain scenarios, voice communication may prove more efficient than text communication as information can be exchanged immediately. Nevertheless, both voice and text communication can be effective for decision-making, on-the-spot brainstorming, and exchanging information to effectively accomplish tasks.

Overall, remote synchronous communication has emerged as a valuable and efficient method for immediate audio and text exchange; however, it is important to recognize the limitations posed by the lack of visual cues. While it enables real-time communication, the absence of facial expressions and body language can impede accurate interpretation and understanding of messages.

2.2.3 Remote Asynchronous Communication

Remote asynchronous communication involves individuals or teams located in different locations who communicate without real-time interaction. This form of communication introduces a delay, ranging from seconds to even weeks, as audio or messages are exchanged and require time for review or a response. Due to the absence of visual cues and real-time feedback, remote asynchronous communication presents significant challenges that impact teamwork [36].

For long-duration space missions, such as the upcoming mission to Mars, it is expected and unavoidable to experience communication delays due to current technological limitations [36]. Consequently, numerous challenges will arise that impact the dynamics between MC and the crew, making effective collaboration and a safe, successful mission more difficult to achieve. While some research has been conducted, our understanding of the specific impact of communication delays on the dynamics between MC and the crew is still limited [36]. The challenges associated with remote asynchronous communication will be further discussed in the following section (Section 2.3). In this discussion, the term 'communication delay' will be used for remote asynchronous communication.

2.3 Challenges of Communication Delay

2.3.1 Message Out of Sequence and Step-ons:

Structured communication plays a vital role in fostering mutual understanding between MC and the crew during space missions. However, communication delay introduces several challenges that need to be addressed. One such challenge is the occurrence of messages being received out of sequence. Due to the delay in transmission, messages may arrive in a different order than intended, leading to confusion and making it challenging for MC to grasp the crew's needs accurately. Another challenge is step-ons, which are interruptions or overlapping transmissions that can happen when multiple individuals attempt to speak simultaneously. This can occur when MC and the crew are unaware that others are trying to communicate at the same time [13].

Moreover, an increase in communication delay can further complicate the situation by creating uncertainty about message reception. In such cases, it becomes difficult to determine which messages have been successfully received, potentially leading

to misunderstandings, repetitive exchanges, frustration, communication breakdown, heightened cognitive load, and decreased productivity [39].

In their study conducted in 2016, Fischer and Mosier aimed to investigate the impact of communication delays on team performance during space missions. The research involved collaboration between the University of California, Santa Barbara, and NASA's Ames Research Center, with a series of experiments conducted to examine the effects of communication delay across various communication types.

One of the experiments included a laboratory study with four teams consisting of MC personnel and astronauts from NASA. Each team comprised eight MC personnel and four crew members. Over a two-day period, the teams participated in six simulated space missions, each lasting two hours and involving the completion of 12 activities. These activities encompassed 11 routine maintenance tasks and one ill-defined task, which could be either a medical emergency or a system failure.

To ensure impartiality, the sequence of communication delays was predetermined, with one mission featuring a 300-second delay and another mission featuring a 50-second delay. Additionally, the occurrence of medical emergencies and system failures was evenly distributed among all teams.

The researchers discovered that communication delays among the teams resulted in various challenges, such as step-ons, messages being out of sequence, and disruptions in turn-taking. These challenges hindered mutual understanding and necessitated extra turns to address the issues, thereby increasing the cognitive workload and time requirements for the team. Moreover, team members had to manage ongoing conversations, potentially resulting in other events taking precedence over ongoing communications.

2.3.2 Lack of Situational Awareness and Feedback:

Situational awareness plays a crucial role in effective communication. However, communication delays pose a challenge for both MC and the crew, as real-time interaction is limited, impacting their ability to develop a shared understanding [13]. The absence of situational awareness can result in minor issues and frustrations, but it can also have severe consequences. In a space mission, significant delays can cause lack of situational awareness, hindering the understanding and resolution of critical situations. This lack of situational awareness becomes particularly critical in emergencies, jeopardizing the safety of astronauts and the overall mission's success. Furthermore, the lack of situational awareness can lead to a widening gap between MC and the crew, as the crew may hesitate to provide further updates due to the time-consuming nature of aligning everyone's understanding.

Researchers from the University of Southern California and NASA's Johnson Space Center conducted a study on the ISS involving three astronauts and 18 MC personnel. The study aimed to examine the impact of communication delays on team performance. The findings revealed that situational awareness was a significant challenge that hindered the crew's performance. One astronaut expressed frustration, stating that tasks relying on ground communication resulted in substantial time loss. The communication delays led to reduced communication between MC and the crew, impeding their effectiveness and ability to accomplish objectives [40].

Similarly, a study conducted by researchers from the University of California, Santa Barbara, and NASA's Ames Research Center revealed that the crew faced challenges with situational awareness when communicating with MC. One of the key difficulties they encountered was in correctly identifying themselves or others during communication, leading to a lack of mutual understanding [39]. In time-critical and high workload situations, this ambiguity and misunderstanding can have serious consequences. When individuals fail to accurately interpret the identity of the speaker or

recipient of a message, misunderstandings can occur. These misunderstandings can undermine MC's ability to perceive, understand, or anticipate emerging situations accurately, potentially resulting in errors, accidents, and jeopardizing the safety of the crew and the mission's success [13].

Furthermore, the absence of feedback and support can further compound the challenge of maintaining situational awareness. Effective teamwork between MC and the crew relies heavily on the exchange of feedback and support. Timely and constructive feedback, as well as supportive interactions, are crucial for the crew to perform at their best. However, communication delays pose a significant obstacle to receiving feedback and support in a timely manner. Real-time discussions on progress, addressing questions, and providing updates on performance become impractical. The lack of adequate feedback and support can leave the crew struggling to identify areas for improvement, lacking necessary guidance and resources, and experiencing frustration and a sense of insufficient support, all of which can have a detrimental impact on their mood and overall performance [39]. Moreover, without timely feedback, issues may go unaddressed, making it challenging to adapt and ensure ongoing progress.

2.3.3 Crew Autonomy and Detachment:

Effective communication plays a crucial role in mitigating a range of potential issues, including a lack of situational awareness, misunderstandings, wasted time, increased cognitive load, frustration, and impaired task performance [13, 39, 40]. When the crew refrains from seeking help due to time constraints and frustration, it can lead to unaddressed dangerous situations [40]. Given the inevitable communication delays during the Mars mission, the crew must adapt to become more autonomous. They will be actively involved in the decision-making processes, particularly in unexpected and emergency events, instead of solely relying on MC [41]. However, this transition may introduce challenges, such as communication breakdowns, misunderstandings, and conflicts between MC and the crew. Moreover, these challenges can

foster feelings of detachment and isolation within the MC-crew dynamic, potentially leading crew members to work and communicate amongst themselves and becoming less dependent on MC when they should be reliant. This decline in teamwork, overall performance, and crew morale [40, 13] can result in misinformed decision-making and missed opportunities, ultimately jeopardizing the mission's outcome.

In the HERA mission, conducted at the NASA Space Center, communication delays of 10 minutes and blackouts were tested during missions [42, 20, 10, 43]. These studies involved eight space mission simulations with a crew of four researchers who acted as astronauts [43]. Surveys were administered to the crew members to gather insights about their interaction with MC.

In a mission involving untrained crew members, the researchers observed a decreased willingness to communicate with MC for guidance during communication delays. As a result, the crew failed to comply with procedures and performed tasks incorrectly, such as skipping steps during a medical simulation. Consequently, they required additional assistance from MC, leading to increased task duration. The crew's response to the communication delay prevented MC from intervening, leaving them with a sense of exclusion [43].Furthermore, in the NEEMO mission, a lack of communication due to a one-second delay resulted in a breakdown of communication, rendering a task unsuccessful during an emergency event [12]. This demonstrated the significant challenge even a slight delay can pose.

The Mars500 project, carried out by the Institute for Biomedical Problems in Russia, encompassed three Mars mission simulations: a 14-day pilot study, Mars105, and Mars520. Researchers identified significant challenges in coordination between MC and the crew during the Mars520 mission, due to communication delays [44]. This delay resulted in impaired decision-making, often relying on assumptions instead of shared mental models, and causing frustration between MC and the crew [44]. Furthermore, as the crew became more independent, they also stopped seeking MC for

guidance, instead they took the initiative to solve their own problems. Additionally, the SIRIUS conducted a four-month-long mission at the same location, testing a five-minute communication delay. The study found that the crew did not contact MC for assistance during the mission [14].

2.4 Protocols

To ensure the safety and success of a Mars mission, effective communication is crucial in addressing the challenges posed by communication delay. In studies where communication delay scenarios were implemented, researchers have developed and tested various protocols to mitigate these issues. While some protocols have demonstrated effectiveness, it is important to note that not all have been equally successful in addressing the challenges of communication delay. Therefore, further research and refinement are necessary to continuously improve these protocols and adapt them to the unique demands of future Mars missions.

These protocols can be categorized into the following groups: preflight training, message clarification, end-message marker, debriefs, and sender and recipient identification. Each of these protocols plays a significant role in fostering effective communication during Mars missions. In the following section, we will discuss each of these protocols and explore their significance in promoting effective communication between MC and the crew.

2.4.1 Preflight training:

Preflight training plays a crucial role in mission preparation by familiarizing crew members with communication protocols to effectively address challenges during the mission. An example from the HERA mission illustrates the significance of preflight training. Despite the relatively short duration of 30 to 60 minutes, the crew demonstrated a high compliance rate (90%) with the protocols. This highlights the effec-

tiveness and impact of even brief preflight training in facilitating interaction between the MC and the crew [26].

2.4.2 Message clarification:

Clear communication, such as specifying the topic, repeating critical information, and tracking the time of the message, has also been identified as important protocols to combat communication delays [10, 43]. One key protocol is specifying the topic of conversation. By clearly defining the subject matter, the conversation remains focused and relevant to the task at hand. This helps prevent unnecessary digressions and ensures that everyone stays on track. Another essential protocol is repeating critical information. By reiterating important details, the crew members can be confident that they have received all the necessary information to carry out their tasks effectively. This redundancy acts as a safeguard against missed or misinterpreted information. Additionally, tracking the time of messages is important for maintaining an orderly conversation thread. Knowing the sequence of messages allows the receiver to understand the context and respond accordingly. This time tracking contributes to the overall efficiency and coordination of the team. During the NEEMO and HERA missions, these protocols have proven effective in reducing misunderstandings between the MC and the crew. By implementing clear communication practices, the missions achieved successful outcomes through improved information exchange and enhanced teamwork [12, 42].

2.4.3 End-of-message marker:

One protocol implemented in studies to facilitate message sequencing involves the use of end-of-message markers, such as 'over' and 'thank you.' This protocol was also implemented in the ISS communication delay study, where its effectiveness was observed. However, researchers discovered that it was less effective during certain communication delays [39]. Specifically, although this protocol proved effective for long communication delays, it was not consistently followed for short delays [39]. This

suggests that end-of-message markers may not be necessary for certain durations of communication delays. Nevertheless, it remains crucial to determine when this inconsistency is acceptable and when it is not, considering specific durations and situations.

2.4.4 Debriefs:

To ensure effective and safe operations, joint training protocols have been tested in HERA and NEEMO missions. It is important to note that NEEMO had participants from NASA, ESA, Canadian Space Agency (CSA), and Japan Aerospace Exploration Agency (JAXA) [10]. Guided team debriefs have been identified as an effective method for enhancing psychological safety, resilience, and teamwork, resulting in improved team performance. According to crew feedback, the debriefing process helped create an environment of honesty and comfort that encouraged crew members to openly discuss issues they may have otherwise been hesitant to share. This is crucial in preventing interpersonal issues that can impact the overall performance and safety of the MC and the crew [26]. As Mars missions will require increased autonomy, research into effective debriefing strategies remains essential to maintaining teamwork and preventing conflicts throughout the mission.

2.4.5 Sender and recipient identification:

The importance of proper identification in communication between MC and the crew cannot be overstated, especially in the absence of face-to-face interaction. As noted by Fischer and Mosier (2016), without clear identification, MC may not be able to respond promptly to crew members in need of assistance, potentially compromising safety, and efficiency. To address this issue, a protocol was implemented instructing the crew members to identify themselves when communicating with MC. While this was generally effective, there were instances where crew members failed to do so, causing confusion, and impairing mutual understanding. This is a significant concern, particularly in emergency or high-workload situations where even minor miscommu-

nications can have serious consequences [39].

Effective communication is crucial for the success and safety for the Mars mission, as communication delay can present significant challenges. To mitigate these challenges, several protocols have been developed and tested in several studies. Some of these protocols have proven effective in reducing misunderstandings and enhancing teamwork, resulting in successful missions. However, it is important to acknowledge that the effectiveness of specific protocols may vary depending on the unique circumstances of each situation. Chapter 5 will delve into ways to enhance these communication protocols, aiming to further improve communication effectiveness and ensure mission safety.

2.5 Research limitations:

Our understanding of effectively teamwork within MTS is still limited, particularly in the context of spaceflight MTS. Effective communication is a key factor in enabling successful collaboration within MTS. Both MC and the crew rely on effective communication to carry out their mission safely and successfully. However, communication delay, a significant challenge during the upcoming Mars mission, will impact the communication between MC and the crew.

Despite recognizing the impact of communication delay, research in this area has been limited in scope, particularly in investigating its effects on MC. This gap in understanding hinders our ability to comprehend how communication delay affects both MC and the crew. Future studies should include MC as an integral team member, as they will also be affected by communication delay. To promote effective teamwork between the crew and MC, protocols have been developed, but their effectiveness in various situations and durations requires extensive research.

Ultimately, comprehensive research in this area will enhance teamwork, ensure

safety, and contribute to mission success. The next Chapter outlines the methods that are employed to address reducing these research limitations.

Chapter 3

Methods

The data for this thesis is derived from a comprehensive review of existing literature on communication delay, encompassing both analog and ISS studies. The selection of relevant studies was based on a thorough literature search employing appropriate keywords to refine the scope of the investigation. The chosen studies were evaluated for their relevance to communication delay, their impact on the effectiveness of the MC team as a cohesive unit with the crew, and the protocols employed to address challenges arising from communication delays.

Furthermore, this study will analyze the protocols that were tested in these studies. Due to the proprietary nature of space organization protocols, these studies provide valuable insights into the protocols used in space missions. By analyzing these protocols, we can better understand the strategies and techniques used to manage communication delays and improve the effective communication between MC and the crew.

We searched the following databases for studies: PubMed, JSTOR, ScienceDirect, sage journals, frontiers, NASA, and Google Scholar. We used the following search terms: "team dynamics," "multi-team systems," "communication delay," "analog studies," "mission control," "flight control," "astronauts," "crew," "interpersonal stressors," "psychological stressors," “psychosocial stressors” , “communication pro-

tocols" "tone", "remote synchronous communication," "remote asynchronous communication," "international space station," "NEEMO??," "NASA," "Mars500," "Mars simulation," "HERA," "Hi-SEAS," "SIRIUS" "mission support," and "mission control center."

We included studies that met the following criteria: (1) conducted in the NEEMO, Mars500, HERA, Hi-SEAS, SIRIUS and ISS, (2) investigated communication delay (3) published in English, (4) peer-reviewed, (5) quantitative or qualitative in nature, and (6) provided sufficient detail to allow for analysis. Studies were excluded if they did not meet these criteria.

3.1 Data Analysis:

The data analysis presented is the result of a qualitative analysis of existing data on the impact of communication delay during analog and ISS missions. Although the existing data analyzed is primarily focused on the impact of communication delay on the crew, this thesis aims to examine the impact of communication delay on MC's role, and propose a new protocol and provide recommendations for communication delay protocols.

3.2 Methods:

This research involved a comprehensive analysis of studies that explored communication delay scenarios, ranging from delays of a few seconds to as long as 20 minutes. These studies examined missions of different durations, ranging from short 60-minute missions to long-duration missions lasting up to a year and a half (520 days). The participants in these studies included current and former astronauts, MC personnel, and astronaut-like individuals. The studies encompassed various tasks, including rou-

tine operational tasks and emergency scenarios, conducted under different conditions of crew autonomy.

The studies conducted interviews, surveys, questionnaires were conducted with the participants. Questionnaires were administered to assess emotional state, social climate, and other factors among MC and crew members. These questionnaires incorporated measures such as the Profile of Mood States (POMS), Group Environment Scale (GES), and Work Environment Scale (WES). Some questionnaires were completed before launch, during the mission, and after the mission, providing a comprehensive assessment [30, 15, 40, 13, 41].

The collected data underwent statistical analysis techniques, including mixed-model regression, analysis of variance (ANOVA), and correction methods to minimize the risk of Type I errors. Statistical methods such as ANOVA, factor analysis, and comparison of means were employed to analyze the data and uncover significant patterns and trends. Studies cited in the research [30, 15, 40, 13, 41] utilized these methodologies and statistical analyses to draw meaningful conclusions from the data.

Content analysis was used to transform communication content into quantitatively measurable categories related to coping strategies. This involved categorizing communication into problem-focused and emotion-focused approaches, providing a deeper understanding of coping mechanisms. Additionally, facial expressions and speech acoustic characteristics were examined using software tools to explore non-verbal communication cues. These analyses allowed researchers to gain insights into the communication dynamics and coping strategies of the participants [41].

To further explore anxiety levels, interpersonal preferences, and cohesion, additional tests and questionnaires such as the State-Trait Anxiety Inventory (STAI) and sociometry were employed. These instruments provided valuable insights into the psychological well-being and social dynamics of the participants. The collected data

were subjected to various statistical analysis techniques, including ANOVA, factor analysis, and comparison of means, to draw meaningful conclusions [15].

The communication exchanges between MC and crew members were transcribed and coded to facilitate the analysis of communication process and content variables. Process variables included examining the timing and sequence of team members' contributions to identify instances of out-of-sequence turns and interruptions. Content variables focused on how communication participants identified themselves and their addressees, as well as the strategies employed to confirm understanding and promote mutual comprehension. Researchers used these variables to analyze the communication dynamics between MC and crew members [38, 39].

The impact of communication delays on the role of MC was assessed through feedback gathered from this data collected by with these methods. The research aimed to understand how communication delays affected the effectiveness of MC and its ability to support the crew during tasks of varying complexity. Additionally, the effectiveness of protocols developed to address communication delay challenges was evaluated using subjective ratings and compliance analysis as evaluation methods.

3.3 Research questions:

- How does communication delay impact MC's role as an effective team member with the crew?
- How can protocols be improved to enhance effective communication between MC and the crew?

3.4 Ethical Considerations:

Since this study solely relies on existing data and does not involve the collection of new data from human subjects, ethical considerations are not required. The participants

in the research studies have already provided consent for their data to be used for research purposes. Privacy, anonymity, and confidentiality of the participants' data will be maintained throughout the study.

3.5 Limitations:

The scope of this study is constrained due to the limited data on communication delay in analog and the ISS studies. The small pool of available data on communication delays in analog and ISS missions may affect the analysis of examining the impact of communication delay on the MC's role as an effective team member. Furthermore, this study is constrained by its focus on analyzing existing literature on communication delay in analogs and the ISS, and thus does not encompass the broader range of research on communication delays in other industries related to MC, such as ground control for aviation. While the study provides valuable insights into the impact of communication delays on MC, it is important to note that other factors, such as crew composition and mission objectives, may influence the effectiveness of the protocols in managing communication delay. However, these factors are not addressed or identified in this study.

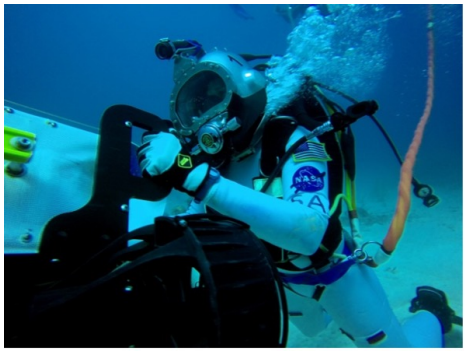

Figure 3-1: Astronaut Serena Aunon carrying out a task at during the NEEMO 20 mission [3]

Figure 3-3: This is a photo of the Hi-SEAS facility Photo credits: NASA) [5]

Figure 3-5: This is a photo of the crew outside the SIRIUS facility Photo credits: NASA) [7]

Figure 3-2: This is a photo of the HERA Facility Photo credits: NASA)[4]

Figure 3-4: This is a photo of the Mars500 facility Photo credits: ESA)[6]

Figure 3-6: This is a photo of the International Space Station Photo credits: NASA) [8]

Chapter 4

Impact of Communication Delay on MC

In this chapter, we delve into the findings of our analysis, which shed light on the challenges posed by communication delays and their impact on the role of MC as an effective team member. By conducting a comprehensive review of literature sources from high fidelity analog and ISS missions, we have identified specific themes that underscore the difficulties faced by MC in understanding the needs of the crew, providing necessary support, and recovering from misunderstandings or inadequate support. These findings have significant implications for the effectiveness of mission operations. In the following sections, we will explore these themes in detail, highlighting their importance in achieving successful mission outcomes.

4.1 MC's inability to sufficiently Understand the Crews Needs:

One notable way that communication delay can hinder MC's effectiveness as a team member is by impeding their understanding of the crew's needs. Delays can cause step-ons, messages to be out of sequence, and no communication. These issues can lead to mistakes, wasted time, and ultimately jeopardize the safety and success of

the mission. For example, according to Fischer Mosier's (2016) study, all four teams of the AMO mission experienced step-ons during their 50-second or 300-second delay missions, resulting in a total of 15 instances of step-ons. These problems made it difficult for MC to fully comprehend the crew's requests and needs. As a result, additional efforts were required to repair communication, leading to increased time and workload for the team.

However, efforts to address misunderstandings in communication can introduce additional challenges. For instance, in response to a misunderstood request, the crew may send multiple short corrective messages. Unfortunately, this approach of sending multiple brief messages instead of a single comprehensive message can lead to more ambiguity and messages being delivered out of sequence, further complicating the situation. The previously mentioned study recorded a total of 49 instances where messages were delivered out of sequence [39]. The occurrence of such messages can lead to critical information being overlooked or improperly acted upon, posing significant risks to both the crew and the mission.

When the crew fails to provide adequate information, this can be attributed to two potential factors: firstly, their need to adapt to correcting the sequence of step-ons and messages, and secondly, their perception that the information may not be of sufficient significance to warrant communication with MC. Consequently, MC is compelled to spend additional time requesting updates, asking follow-up questions, and experiencing a lack of situational awareness. A case study reported by Mosier and Fischer (2021) highlights the impact of such communication inefficiencies, wherein no communication was made regarding the condition of a system involved in an experiment for several weeks, resulting in inefficiencies in MC operations. This lack of understanding caused by communication delays can hinder MC's ability to provide effective support to the crew, potentially leading to a failure to meet their needs. In the following section, we will explore the challenges that MC may face in providing support to the crew in the due to their lack of situational awareness.

4.2 MC's inability to Fully Support the Crew:

During the Mars mission, unexpected events may arise that require immediate attention from the MC. However, if the MC is not aware of the situation, their ability to understand and respond to the crew's needs appropriately may be hindered, further exacerbating the situation. Moreover, communication delay can impact the MC's ability to provide timely support, which can lead to crew frustration or a loss of confidence in the MC's ability to meet their needs. This, in turn, can present further challenges in maintaining effective communication and coordination between the MC and the crew. For instance, in the HI-SEAS Mission IV, crew members reported feeling dissatisfied when their requests were not acknowledged or when the MC was perceived as unresponsive [30].

Furthermore, researchers have observed MCs experiencing stress during the mission because they were unable to provide real-time intervention as they traditionally would in current mission [45]. This lack of immediate assistance affected their ability to support the crew. Additionally, breakdowns in communication between the crew and MC can occur when they are unable to immediately confirm their opinions, as shown in an analysis of communication data from the Mars-500 experiment [15]. Such breakdowns can lead to mistrust and further challenges in maintaining effective communication and coordination between the crew and MC. Elevated levels of tension were reported by the MCs during the Mars105 mission [15]. It is crucial for MCs to find ways to maintain situational awareness, provide timely feedback, and minimize communication delays to ensure effective support to the crew during the missions. If MC is unable to provide the necessary support to the crew, it can lead to a decrease in the crew's reliance on them, which in turn may render the role of MC less effective. This will be discussed in the following section.

4.3 MC's Inability to Recover from Misunderstandings and Inadequate Support:

Effective support from MC is critical throughout the entirety of a space mission. However, one of the challenges that can hinder MC's effectiveness as a team member is their difficulty in recovering from misunderstandings or providing inadequate support to the crew during communication delay. When communication delay occurs, the crew is expected to become more autonomous in their decision-making. However, if MC cannot fully comprehend or provide the necessary support, the crew may become even more reliant on themselves and experience displacement from MC. The phenomenon of displacement is when the crew members feel disconnected or disengaged from the MC [30]. This can lead to the crew disregarding the role of MC, which can render it less effective as a team member. The crew's increasing autonomy can prevent MC from making effective decisions based on a clearer understanding of the situation on board, making it difficult to provide practical recommendations [41].

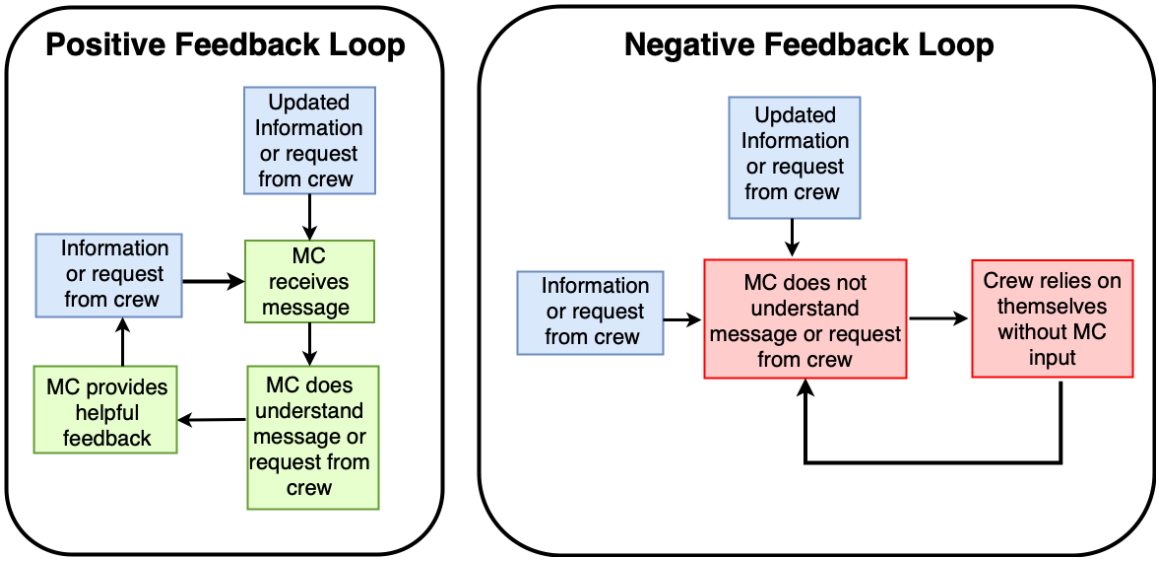

Figure 4-1: This diagram illustrates the communication loop between the crew and the Mission Control (MC) during a space mission.

There are two communication scenarios that the crew can choose from after sending or requesting information from MC. These scenarios are illustrated in Figure 4-1 above. The communication loop starts with the crew providing information to the

MC. Depending on whether the MC understands the information or not, this is were the two possible scenarios are presented. If the MC doesn't understand the information, the crew has two options: they can either re-explain or request the information again and wait for the communication delay, or they can choose to rely on themselves and make autonomous decisions. If at any point in the communication loop, there are misunderstandings or inadequate support, the crew may become more autonomous in their decision-making, leading to a detachment from MC, possible failures, and a less effective role for MC as a team member. However, if there are still misunderstandings or inadequate support, the loop goes back to the beginning, with the crew providing information to the MC, and the cycle continues until effective communication and support are achieved.

The other scenario occurs when the MC comprehends the information, enabling effective communication and support. In this case, the loop continues as the MC receives new information and requests from the crew. This results in a successful outcome. Overall, the communication loop highlights the importance of clear and effective communication between the MC and the crew to ensure successful mission outcomes. It also emphasizes the need for the MC to be adaptable and responsive to the crew's needs, as well as the importance of maintaining a strong team dynamic throughout the mission.

The increase in crew autonomy is expected under communication delay and has been observed during NEEMO Missions 12 and 13, and Mars105 [15]. Crew members tend to react positively to autonomous conditions, reporting positive moods, personal discovery, and innovation. However, when MC misunderstands or provides inadequate feedback due to communication delays and is unable to quickly recover to address this mistake, it can lead to the crew relying more on their own decision-making, resulting in reduced MC input [30].

This detachment can lead to significant issues, as the crew may become accus-

tomed to making decisions independently without considering MC input, ultimately hindering the mission's success. This was evident during the Mars-500 experiment, where crew members made independent decisions without informing MC of their needs and problems [40]. Additionally, as seen in the medical simulation failure mentioned in Chapter 2, the crew's failed to follow procedures provided by MC and as a result they performed the task incorrectly and required additional assistance from MC [43].

Therefore, it is crucial to develop a comprehensive understanding of how communication delays impact the MC's effectiveness as a team member. These delays directly impede the MC's ability to provide vital support to the crew. Recognizing that the crew alone cannot successfully accomplish the mission without the assistance of the MC is essential. To mitigate this issue, it is imperative to explore and improve protocols that address communication delays. These protocols, which will be elaborated upon in Chapter 5, have the dual aim of improving the MC's ability to collaborate effectively as a valuable team member and facilitating effective communication between the MC and the crew.

Chapter 5

Communication Delay Protocols

In this chapter, we a propose protocol and recommendations that should be considered for future studies to address the challenges associated with communication delays to enhance the effectiveness of both MC and the crew as team members. We conducted a comprehensive review of literature sources from high-fidelity analog and ISS missions to gather relevant data. Our analysis of the data has led us to propose a new protocol centered around tone, as well as two recommendations for improving current protocols focused on communication delay. These proposals should be considered for implementation to enhance the effectiveness of protocols used to address communication delay.

5.1 Tone Protocol for Effective Communication:

One important aspect that is often overlooked in communication protocols is the significance of tone. In this thesis, tone refers to the speaker or writer's character of language, expressed through inflection, word choice, and phrasing, which conveys their feelings, attitude, or opinion towards a subject or audience in verbal or written communication. The tone can significantly impact effective communication and consequently affect the performance of the crew and the mood of the MC. Therefore, it is crucial to have a protocol in place that helps facilitate effective communication

between MC and the crew, regardless of their mood.

Using a positive tone has been shown to improve performance. For example, in the HI-SEAS Mission IV, MC communicated in an autonomy-supportive manner, providing the crew with options and action choices, explaining their rationale, and taking personal preferences into account [45]. They used inviting language such "you can", showed empathy, and allowed the crew to vent freely when needed, resulting in improved motivation, and performance. This demonstrated that tone is crucial for maintaining effective communication to enhance safety and success for the mission. However, when autonomy in decision-making is restricted or urgent help is needed from MC under communication delay, the manner of communication can pose challenges and inadvertently create a negative tone.

During the Mars520 mission, a notable instance occurred where the MC was unable to respond to the crew promptly. This communication delay led to increasing frustration among the crew, negatively impacting their mental well-being. As a consequence, the crew members exhibited signs of frustration and conveyed their dissatisfaction by repeating questions back to the MC with an attitude.[44]. This frustration was particularly evident during cargo operations, where timely feedback was crucial [40]. If MCs regularly receive negative comments or attitudes from the crew, it can negatively impact the MCs mood and their effectiveness in helping the crew.

Furthermore, the implications of delayed responses extend beyond frustration. The crew's interpretation of the MC's delayed communication can lead them to perceive a lack of care or concern from the MC's side [13]. This misinterpretation further strains the crew-MC relationship. Late responses can also disrupt task execution, particularly when the crew has already initiated a requested activity [13]. Such situations can result in heightened frustration and irritability among the crew, compounding the challenges faced by both the crew and the MC [13].

To address this, implementing a protocol that promotes positive and constructive communication is essential. The sample replacement messages provided in Table 1 serve as valuable examples to illustrate how positive communication can foster a harmonious and productive environment for the MC and the crew to collaborate effectively. By practicing responses, the MC and the crew can develop the skills needed to maintain a positive and supportive working dynamic, leading to improved mission outcomes.

Question Class	**Negative Tone**	**Replacement Positive Tone**
Lack of response following prompt	“Ronald, you haven’t responded to my message."	“Hi Ronald, I’m still waiting to hear back from you about the medical procedure. Can you please update me?"
MC requesting information	“Inez, I am unable to provide help if you do not provide me information."	“Inez, I need some more information so that I can help you. Can you please provide me with the following?"
Crew challenges MC decision making	“We will make this decision without you."	“Could we move forward with making an independent decision and update you?"

Table 5.1: Sample replacement messages with a positive tone. Ronald in this case represents MC, and Inez is a member of the astronaut crew.

5.2 Inconsistent testing of Communication Delay Times:

The delays listed for each mission vary significantly, ranging from as little as 1.5 seconds to as much as 20 minutes, making it difficult to compare data and draw conclusions across studies. Given that studies including communication delay is small, it is crucial that the information on communication delay is comparable. Therefore, standardizing communication delays across all analog and ISS missions will help en-

sure that data collected is consistent and comparable, making it easier to identify common challenges to develop effective communication protocols for future missions. In this section, down below shows the different time delays in each study in Table 5.2.

Mission	**Duration**	**Communication Method**	**Communication Delay**
HI-SEAS	4-12 months	Email	<20 minutes (one way)
HERA	7-45 days	Audio and text	<20 minutes (one way)
NEEMO	3 weeks	Audio, text, and video	50 seconds, 5 minutes, 10 minutes, 20 minutes (one way)
Mars500	Mars500: 14-day pilot study 105-day mission 520-day mission	Email, audio, and video	20 minutes (one way)
SIRIUS	4 months	Email and video	5 minutes (one way)
ISS	>60 minutes	Audio, text, and video	50 seconds (one way)
AMO	2 days		50 seconds, 5 minutes (one way)

Table 5.2: Communication details for different space missions. The table presents the mission names, their durations, communication methods utilized, and the corresponding communication delays (one way) [9, 10, 11, 12, 13, 14, 15, 16].

The impact of communication delays can vary based on their duration. A shorter communication delay may have a relatively minor impact on one team of MC and crew members, while a longer delay has the potential to lead to interpersonal problems within another team. For instance, a team of MC and crew members who have experienced delays of 5+ minutes may be less affected by a 50-second delay, whereas

another team that has only encountered a maximum delay of 50 seconds may experience a more pronounced impact. Furthermore, the presence of multiple variations in delays throughout their mission can further influence how each team of MC and crew members react to the delays. As previously mentioned, the frequency of step-ons during communication was found to vary depending on the length of the delay. For instance, during the 50-second mission, there were 11 instances of step-ons, while there were only four instances during the 300-second mission [39]. Therefore, it is imperative to standardize communication delays in analog and ISS studies to expand our knowledge by providing a more comprehensive understanding of how different delay times impact MC and the crew. This standardization will enable researchers to develop protocols that can effectively address the challenges posed by communication delays.

5.3 Standardization of Communication Delay Protocols:

In order to enhance our understanding and develop effective protocols, the establishment of standardized communication protocols is crucial. These protocols should be universally applicable to studies involving communication delays. As the mission to Mars will involve MCC's and crews from different countries, the presence of standardized protocols becomes even more essential. Such protocols facilitate seamless communication and help mitigate the challenges posed by communication delays within international teams. By implementing standardized protocols, all MCC's and crews involved can operate on a shared framework, promoting cohesion and fostering effective communication practices.

Unfortunately, current research indicates that there is a lack of unified and consistent training protocols among different space agencies, which hampers the establish-

ment of standardized communication practices. According to Anania et al. (2017), flight directors at NASA's MCC undergo different protocol training compared to other MCC's for the European Space Agency and Roscosmos. Additionally, each agency utilizes a variety of communication methods, in addition to traditional audio communication. This diversity in training protocols can lead to challenges in effective teamwork and communication dynamics within multi-agency space missions. When different agencies have undergone different protocol training, it can create discrepancies in communication expectations, procedures, and coordination. Misunderstandings and misinterpretations may arise due to the lack of standardized practices, potentially compromising mission success and safety. Furthermore, the utilization of various communication methods introduces additional complexities. Each agency may employ different communication methods, making it hard to find the most effective one. Inconsistent communication methods can hinder efficient information sharing, decision-making processes, and overall situational awareness among MCCs and crew members from different agencies.

Additionally, it is crucial to acknowledge that there may be circumstances where strict adherence to the communication protocol may not be feasible or appropriate. Emergencies, for instance, may necessitate immediate action that cannot wait for protocol confirmation. In such critical situations, deviations from the standard protocol might be necessary to address the immediate needs. Similarly, for minor disruptions or short delays that do not significantly impact the mission's success, strict adherence to the protocol may not be essential. In such cases, it becomes important to exercise judgment and flexibility in communication practices.

Therefore, while standardized communication protocols are indispensable, it is equally vital to provide crew members with training that enables them to recognize situations when the protocol can and cannot be followed. As mentioned in Chapter 2, the crew exhibited inconsistent use of the end-of-message marker during short delays [39]. Training programs should incorporate realistic scenarios that simulate emergen-

cies and other situations where strict adherence to the protocol may not be feasible.

Crew members should be trained to make prompt decisions while still adhering to the principles of effective communication. This training will foster their ability to assess the context, weigh the risks, and employ appropriate communication strategies in situations that demand deviations from the standard protocol. By providing crew members with the necessary skills and situational awareness, space agencies can ensure that effective communication practices are maintained even in non-standard circumstances.

Additionally, it is crucial for MC to be well-versed in identifying situations where crew members may deviate from the established communication protocols, either due to emergencies or non-significant disruptions. MC plays a pivotal role in supporting the crew's decision-making process and should be equipped with the knowledge and understanding to assess when to provide the necessary support. MC should possess the ability to recognize the context and assess the risks associated with deviating from the protocol. This includes understanding the potential consequences and implications of such deviations on mission objectives, crew safety, and overall communication effectiveness. By having a comprehensive understanding of the protocol and the specific circumstances at hand, MC can provide guidance and support to the crew, ensuring that deviations are made with careful consideration and align with the principles of effective communication.

Moreover, MC should establish positive communication with the crew, fostering an environment where crew members feel comfortable discussing deviations from the protocol and seeking guidance when needed. This proactive communication approach helps build trust and facilitates effective collaboration between MC and the crew during critical decision-making moments.

Therefore, it is imperative to establish new communication protocols that are

inclusive and consistent to mitigate the challenges associated with communication delays. This necessitates the creation of protocols that are tailored to meet the unique needs and demands of multi-agency space missions. To achieve this, extensive research is necessary to thoroughly investigate the existing protocols and identify areas for improvement. By examining the strengths and weaknesses of current protocols, researchers can gather valuable insights to inform the development of new and enhanced protocols.

Chapter 6

Discussion and Conclusion

In this chapter, we present the findings from two distinct result chapters of our research, offering a cohesive conclusion that synthesizes the key insights obtained from the study. Moreover, we propose recommendations for future studies to expand upon this thesis.

6.1 Impact of Communication Delay on MC:

6.1.1 Discussion

The study highlights the critical role of MC as an effective team member alongside the crew, emphasizing the significance of efficient communication between MC and the crew in ensuring the success of the mission. Therefore, it can be concluded that the hypothesis "communication delay will have a significant impact on MC's current role as an effective team member with the crew." is supported by the findings. While the precise nature of MC's role in the specific Mars mission remains unclear, the establishment of protocols emerges as a vital step toward understanding and enhancing the effectiveness of MC in their new role.

6.1.2 Conclusion

In conclusion, the study has shown that communication delays have a significant impact on the effectiveness of MC as a team member with the crew. Communication delays hindered mission control's ability to understand the crew's needs, provide necessary support to meet their needs, and recover from misunderstandings or inadequate feedback. Specifically, the impact of communication delays was observed in compromised mutual understanding, leading to lack of situational awareness. As a result, MC encountered difficulties in providing timely support and making informed decisions for the crew. This heightened the crew's reliance on their own problem-solving abilities, which yielded both successes and failures in their mission.

These challenges highlight the critical role of MC in ensuring the safety and success of the mission. For future studies, the role of MC should be further analyzed in communication delay as it is crucial for ensuring the safety and success of the crew and mission.Additionally, research should be conducted to better understand the challenges MC faces when working with international crews and MCC's under communication delays. This will be important for the success of the Mars mission, which will likely involve international collaboration. It should also be noted that the role of MC will evolve, and that they will not micromanage the crew like they do now. Therefore, more studies need to include how MC's role affects the crew by testing different responsibilities for MC.

6.2 Communication Delay Protocols

6.2.1 Discussion

Based on the presented evidence, the findings support the hypothesis that current research on communication delay protocols in studies lacks consistent implementation and standardization, indicating the need for protocol improvements to achieve more effective communication in future studies. This study introduces a novel pro-

tocol along with two key recommendations to enhance communication delay testing: addressing tone, delay, and standardization.

To foster effective and respectful communication between MC and the crew, it is recommended to implement protocols that specifically target the tone of communication. These protocols can establish guidelines to ensure that interactions are supportive, respectful, and conducive to effective collaboration. Furthermore, standardizing the delay time used in each study that tests communication delay is essential. By employing the same delay time across studies, it becomes significantly easier to compare and evaluate results, enabling researchers to draw meaningful conclusions and identify patterns or trends more accurately. In addition to delay standardization, the study highlights the crucial importance of standardizing protocol training across all studies and other space agencies. This becomes particularly critical for the Mars mission with an international crew. Consistent training protocols will ensure that crew members are uniformly prepared and well-versed in the communication procedures, leading to smoother operations and heightened mission success

6.2.2 Conclusion

Communication delay is a critical issue that must be addressed to enhance the effectiveness of both MC and the crew. Our results suggests that there is inconsistent communication delay testing and limited research on protocols in studies. To address this, we recommend the implementation of protocols that address tone, delay, and standardization. We propose establishing international protocols to ensure standardized communication across studies and agencies, and standardizing communication delays to ensure data consistency. Although it is important to adhere to standardized protocols, it is also essential to train crew members to recognize when the protocol cannot be followed, such as during emergencies or short delays. These efforts will work towards enhancing effective communication, leading to improved mission outcomes during communication delay.

6.3 Recommendations:

For further work, studies should include preflight and joint protocol trainings between MC and the crew as a standard practice to enhance the effectiveness of the protocols utilized in the mission. These trainings will foster collaboration, build mutual understanding, and enable both parties to familiarize themselves with the communication protocols. By implementing this recommendation, significant strides towards improving the studies that aim to understand the impact of communication delay and develop effective protocols that benefit both MC and the crew.

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