Bridging the Delay: ECHO as a Tool for Studying Interplanetary Communication Challenges

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Abstract

This paper introduces ECHO, an open-source graphical user interface (GUI) created to simulate and mitigate interplanetary communication delays in analog space missions. Designed to make research on human factors in high-latency environments more accessible, ECHO provides a flexible platform for testing communication protocols involving text, audio, video, and file exchanges. The tool enhances user situational awareness through features such as indicators for in-transit and out-of-sequence messages, and supports fixed or dynamic Martian light-time delay profiles. This paper describes ECHO's design, novel contributions to delayed communication research, and key insights gathered from its deployment in real-world analog missions.

Keywords: planetary analog, time-delayed communications, communication technology, long-duration spaceflight

Superando el retraso: ECHO como herramienta para estudiar los desafíos de la comunicación interplanetaria

Resumen

Este artículo presenta ECHO, una interfaz gráfica de usuario (GUI) de código abierto creada para simular y mitigar los retrasos en las comunicaciones interplanetarias en misiones espaciales analógicas. Diseñada para facilitar la investigación sobre factores humanos en entornos de alta latencia, ECHO proporciona una plataforma flexible para probar protocolos de comunicación que incluyen

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texto, audio, vídeo e intercambio de archivos. La herramienta mejora la comprensión situacional del usuario mediante funciones como indicadores de mensajes en tránsito y fuera de secuencia, y admite perfiles de retardo de tiempo luz marciano fijos o dinámicos. Este artículo describe el diseño de ECHO, sus novedosas contribuciones a la investigación sobre comunicación retardada y los conocimientos clave obtenidos de su implementación en misiones analógicas reales.

Palabras clave: análogo planetario, comunicaciones con retardo temporal, tecnología de la comunicación, vuelos espaciales de larga duración

弥合延迟：ECHO作为研究行星际通信挑战的工具

摘要

本文介绍ECHO，一个用于模拟和缓解模拟太空任务中行星际通信延迟的开源图形用户界面(GUI)。ECHO旨在使高延迟环境下的人为因素研究更加便捷，它提供了一个灵活的平台，用于测试涉及文本、音频、视频和文件交换的通信协议。该工具通过诸如传输中和乱序消息指示器等功能，增强了用户的态势感知能力，并支持固定或动态的火星光时延迟模型。本文描述了ECHO的设计、其对延迟通信研究的创新贡献，以及从其在真实模拟任务中的部署中获得的关键见解。

关键词：行星模拟，时延通信，通信技术，长期太空飞行

Introduction

Among the many challenges of future human interplanetary missions, communication latency remains one of the most fundamental barriers (Love & Reagan, 2013). The one-way light-time (OWLT) delay between planets renders real-time communication impossible, forcing crews to operate with greater autonomy and limited ground support (Gushin, 2003; Kansas, 2010; Love & Reagan, 2013). This paradigm shift increases workload and stress while reducing situational awareness.

Although latency is an immutable physical constraint, prior research shows it can be mitigated through training, procedures, and technologies specifically designed for delayed operations (Lester & Thronson, 2011; Rader et al., 2013). To study these effects, researchers require tools capable of accurately emulating communication delays in analog environments.

Existing solutions often rely on custom configurations or proprietary systems such as NASA's Playbook, which limit accessibility for broader research.

To address this gap, ECHO (Emulating Communication delays for Human spaceflight Operations) was developed as an open-source, web-based platform for simulating and mitigating delay effects (Schor, 2024). ECHO supports studies of interface design, communication strategies, and human performance in delayed environments. It has been tested and deployed in over ten analog missions at the University of North Dakota's Integrated Lunar Mars Analog Habitat (ILMAH).

Objective

The objective of this study is to present ECHO as a tool for simulating, studying, and mitigating interplanetary communication delays in analog missions. By offering an open, extensible, and easy-to-deploy platform, ECHO lowers barriers to research on human factors and decision-making in high-latency environments.

Background

Before the advent of specialized platforms, analog missions typically relied on adapting commercial off-the-shelf (COTS) software or assembling complex systems to simulate latency. Early missions such as NEEMO and D-RATS used Linux-based channel emulators with VoIP applications like VCOM and XMPP servers for text messaging (Rader et al., 2013; Downs, 2012). Although functional, these systems lacked features critical for long-duration use such as message notifications, integrated audio and video playback, and effective tools for organizing delayed conversations. Their complexity also limited reproducibility and accessibility for external researchers.

NASA later developed Playbook, an integrated mission planning and communication platform designed to operate under simulated delays (Marquez et al., 2013; Kanefsky et al., 2017; J. Gale et al., 2018). Its dual-server architecture, with one instance at the habitat and another at Mission Control, effectively simulated OWLT by holding messages until their delivery time expired (Marque, Hillenius, Deliz, et al., 2019). Features like visual countdown timers, auditory notifications, and message prioritization improved usability (Marque, Hillenius, Deliz, et al., 2019). However, the system's public-only chat model and reliance on centralized infrastructure made it less flexible for independent research teams.

Other tools, such as Braiding, explored structured conversation management by organizing exchanges into topic-based threads or "braids" (Fischer et al., 2023). This approach reduced confusion caused by out-of-sequence messages but introduced rigid interaction rules that some users found restrictive. These systems highlighted the need for a more adaptable, open-source solution capable of supporting diverse experimental designs—needs directly addressed by ECHO.

Methodology

ECHO's development and evaluation followed a mixed-methods approach during three consecutive missions at UND's ILMAH facility. Participants interacted with two interface variants—one basic (Interface A) and one enhanced (Interface B)—to assess the impact of mitigation features.

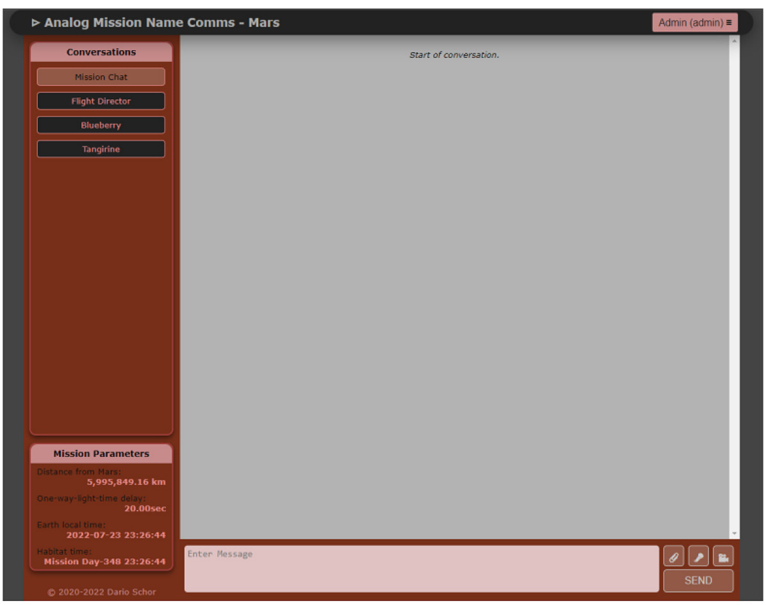
Data collection included post-phase surveys using the System Usability Scale (SUS) and an Acceptability Scale to evaluate usability and willingness to adopt the tool (Brooke, 1996; Abercromby et al., 2013). A final Delphi study, conducted across all 19 participants, consolidated findings and ranked the usefulness of ECHO features and future improvements. Quantitative data were analyzed with descriptive statistics, while qualitative feedback provided context for interpreting user responses.

ECHO Design and Implementation

ECHO was designed as a three-tier web application (Data, Application, and Presentation tiers) hosted on a single server (Schor, 2024). Unlike dual-server systems that separate habitat and mission control instances, ECHO integrates delay simulation within one environment to simplify deployment and synchronization. The system uses Server-Sent Events (SSEs) to push real-time updates to clients and accurately model OWLT delays. While the analogs relied on a fixed delay, the system also allows users to define time delays as a function of time to mimic transit times or to use a Martian delay profile that is based on propagated orbit models useful for educational outreach environments (Schor, 2024). Messages are ordered based on local receipt time, ensuring users see information in the sequence available to them during operations.

The GUI was developed to manage the cognitive load of delayed communication. Visually, it utilizes red and blue pallets to distinguish the interface for those on a remote planet and Earth respectively. Practically, It supports text, audio, video, and file exchanges in both public and private channels, integrating all communication media into one environment (Schor, 2024). ECHO's design focuses on enhancing situational awareness through key features shown in Table 1.

(a) Mission Control Interface using blue tones



(a) Analog Habitat Interface using red tones

Figure 1: ECHO Interface.

Table 1: ECHO features for enhancing situational awareness in high latency environments

Category	Feature	Purpose
Delay Simulation (Figure 2)	Visual progress bar	Displays the elapsed time for messages currently in transit, filling up to show the proportion of transmission time completed. This feature serves as a coarse reminder of the delay, intended to reduce users' mental workload by helping them estimate delivery time and plan activities. It updates at 1 Hz and was ranked as the most useful current feature by study participants.
	Timestamped send/receive	Shows both the message send time and the estimated delivery time next to the message status (e.g., "transit" or "delivered"). This provides essential fine-grained context for high-latency conversations and was ranked the second most useful feature. The status text "delivered" indicates the message reached the other site, but not necessarily that the user has read it.
Organization (Figure 3)	Conversation threads	Supports creating sub-channels (or threads) to categorize discussion topics. This is intended to organize the conversational flow and declutter the main chat by grouping messages on specific topics.
	Unique message identifiers	Assigns unique sequential IDs based on the sender's site (e.g., MCC-n, HAB-n) for each conversation. This was introduced as an alternative numbering system to aid conversation tracking without the need for timestamps that are planet dependent. The identifiers are unique for each message thread.

Mitigation Indicators (Figure 4)	Out-of-sequence flag	A novel visual cue (small icon) that flags messages received chronologically by timestamp, but which were sent out-of-order, meaning the sender composed the message without knowledge of another message already propagating through the delay. This feature directly addresses what out-of-sequence problems (Love & Reagan, 2013).
	Important message flag	Allows users to flag time-sensitive communications. The GUI applies prominent formatting and a more jarring sound to draw immediate attention. This feature was ranked third most important, confirming the need for tools to convey urgency.
Usability	Integrated media & notifications	Provides capability to exchange text, audio, video, and file attachments all within the single platform. Includes sound (a small chirp) and browser badge alerts to notify users of new messages.
	Markdown support	Enables users to preview and apply basic text formatting (e.g., bold, italicize, lists, links) by typing Markdown syntax into the message box.

The administrator interface allows for all mitigation features to be enabled or disabled individually, allowing researchers to isolate and study their effects. The system also provides export options for post-mission analysis.

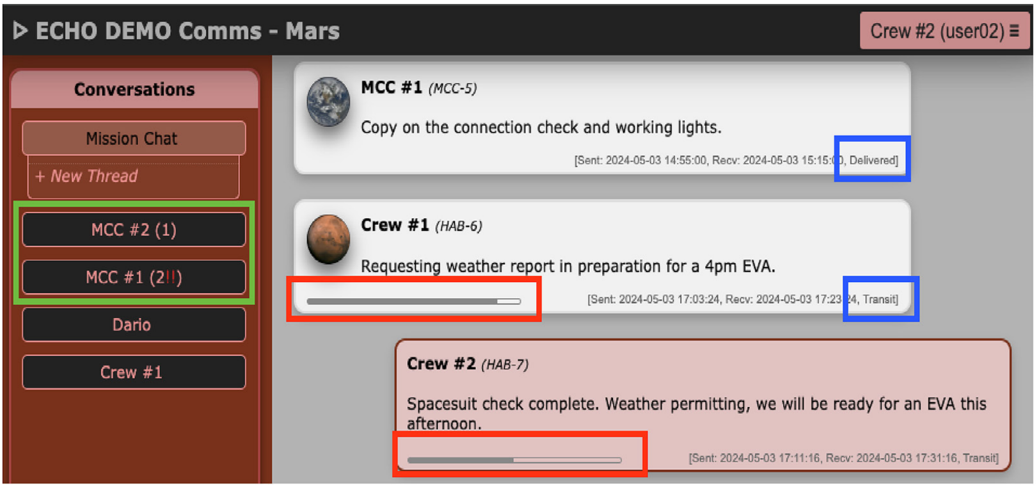


Figure 2: ECHO interface illustrating message delivery status, progress bars, and unread message indicators. The blue boxes show delivery states ("in transit" and "delivered") displayed beside each message timestamp. The red boxes highlight progress bars for messages HAB-6 and HAB-7, sent by different crew members, which are expected to arrive in approximately 3 and 10 minutes, respectively, under the 20-minute OWLT delay used in this example. Once a message is delivered, as shown for MCC-5, its progress bar disappears. The green boxes indicate unread message counts, showing one unread message in the private chat with "MCC #2" and two unread messages with "MCC #1," one of which is marked high-priority by red double exclamation marks.

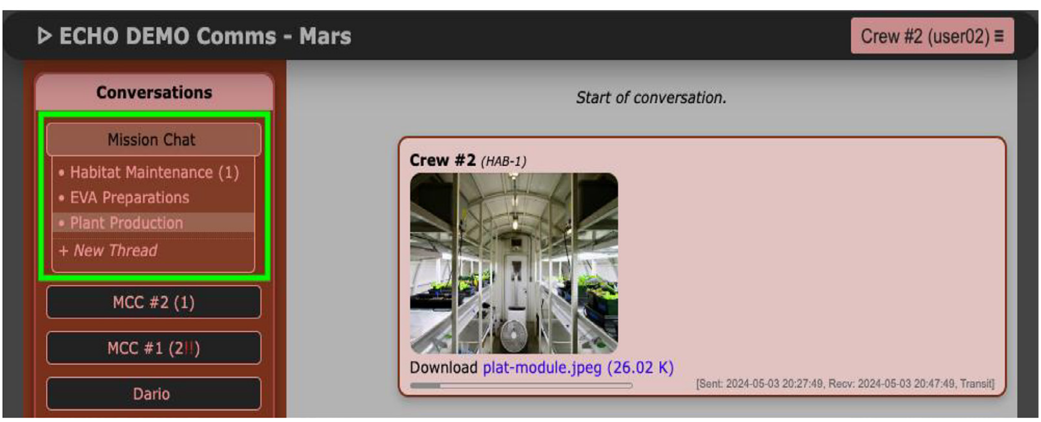


Figure 3: ECHO interface showing threaded conversations for organizing discussion topics. The conversation panel (green border) displays the control to create a new thread, the list of existing threads, and the currently active "Plant Production" thread. The chat panel on the right shows the message exchange within the active thread.

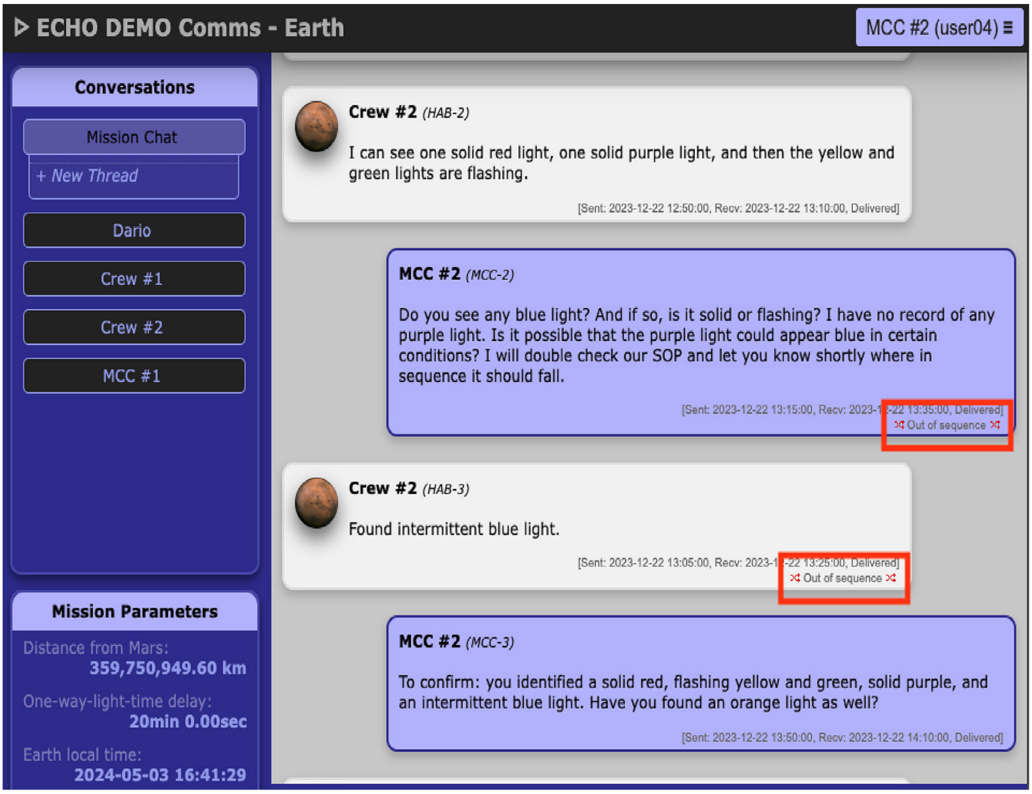


Figure 4: ECHO interface illustrating out-of-sequence message indicators. In this example, message HAB-3 was sent before MCC-2 but received afterward due to transmission delay, triggering the out-of-sequence notification from the mission control perspective.

Results and Discussion

ECHO's usability was evaluated across three ILMAH missions (XV–XVII), yielding 56 total survey responses. The average System Usability Scale score exceeded the 68th percentile benchmark, indicating above-average usability despite the complexity of delayed communication operations. Acceptability ratings were generally positive but highlighted areas for improvement, such as mobile compatibility and search functionality (Schor, 2024).

Figure 5 shows the ranking of user features. The visual progress bar and timestamped delivery indicators consistently ranked as the most valuable features, helping users visualize message flow and maintain awareness of delay effects. The important message flag was also widely praised for effectively drawing attention to critical communications.

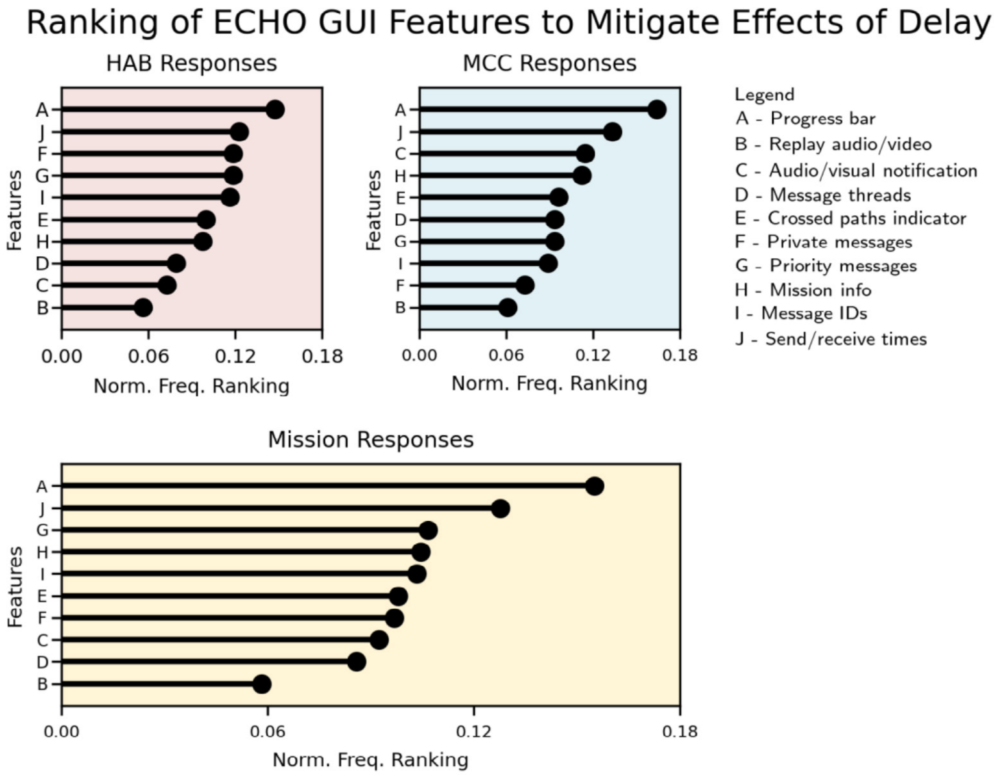


Figure 5: Results from Delphi study where participants ranked of ECHO features helping to mitigate effects of delay.

Role-based differences emerged: mission controllers valued audiovisual notifications for multitasking, while crew members prioritized private messaging for personal and operational exchanges. Participants also suggested improvements such as message search tools, bookmarks, and templates for common messages, indicating the need for more advanced information management within the system.

Conclusions

This study introduced and evaluated ECHO, an open-source tool designed to simulate and mitigate interplanetary communication delays. Results from multiple analog missions demonstrated that carefully designed interfaces can reduce confusion, improve awareness, and enhance user confidence when operating under high-latency conditions. ECHO's visual delay indicators and priority messaging tools were especially effective in helping users manage expectations and maintain communication flow. Its open-source, web-based architecture enables broad adoption and customization for future analog and educational research.

Future work will focus on implementing advanced search and message management features and improving mobile interface. Since its initial release in 2021, ECHO has been used in more than ten missions at the ILMAH missions, two missions at Flashline Mars Arctic Research Station (FMARS), and continues to serve as a practical foundation for studying the human and operational impacts of interplanetary communication delays.

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References

Abercromby, A. F., Chappell, S. P., & Gernhardt, M. L. (2013). Desert RATS 2011: Human and robotic exploration of near-Earth asteroids. *Acta Astronautica*, 91, 34–48. doi: 10.1016/j.actaastro.2013.05.002

Brooke, J. (1996). SUS: a quick and dirty usability scale. *Usability Evaluation in Industry,* 189.

Downs, M. (2012). Tools of the trade with time delayed communications. In *Technical Interchange Meeting on the Impacts of Time Delay on Human Exploration Communications*.

Fischer, U., Mosier, K., Schmid, J., Smithsimmons, A., & Brougham, R. (2023). Braiding – a novel approach to supporting space/ground communication under signal latency. *Acta Astronautica*, 207, 411–424. doi: 10.1016/j.actaastro.2023.03.023

Gale, J., Karasinski, J., & Hillenius, S. (2018). Playbook for UAS: UX of goal-oriented planning and execution. In D. Harris (Ed.), *Engineering psychology and cognitive ergonomics* (pp. 545–557). Springer International Publishing. doi: 10.1007/978-3-319-91122-9_44

Gushin, V. (2003). Problems of distant communication of isolated small groups. *Human Physiology*, 29, 548–555. doi: 10.1023/A:1025803614564

Kanas, N., Saylor, S., Harris, M., Neylan, T., Boyd, J., Weiss, D. S., ... Marmar, C. (2010). High versus low crewmember autonomy in space simulation environments. *Acta Astronautica*, 67(7–8), 731–738. doi: 10.1016/j.actaastro.2010.05.009

Kanefsky, B., Zheng, J., Deliz, I., Marquez, J. J., & Hillenius, S. (2017). Playbook data analysis tool: Collecting interaction data from extremely remote user. In *Proceedings of the Human Factors and Ergonomics Society 61st Annual Meeting* (pp.

303–313). doi: 10.1007/978-3-319-60492-3_29

Lester, D., & Thronson, H. (2011). Human space exploration and human space flight: Latency and the cognitive scale of the universe. *Space Policy,* 27(2), 89–93. doi: 10.1016/j.spacepol.2011.02.002

Love, S. G., & Reagan, M. L. (2013). Delayed voice communication. *Acta Astronautica*, 91, 89–95. doi: 10.1016/j.actaastro.2013.05.003

Marquez, J.J., Pyrzak, G., Hashemi, S., McMillin, K.,&Medwid, J. (2013). Supporting real-time operations and execution through timeline and scheduling aids. In *43rd International Conference on Environmental Systems*. doi: 10.2514/6.2013-3519

Marquez, J. J., Hillenius, S., Deliz, I., Zheng, J., Kanefsky, B., & Gale, J. (2019). Enabling communication between astronauts and ground teams for space exploration missions. In *2019 IEEE Aerospace Conference* (p. 1-10). doi: 10.1109/AERO.2019.8741593

Rader, S. N., Reagan, M. L., Jonoiko, B., & Johnson, J. E. (2013). Human-in-the-loop operations over time delay: Lessons learned. In *43rd International Conference on Environmental Systems* (pp. 1–33). doi: 10.2514/6.2013-3520

Schor, D. (2024). *ECHO: A Graphical User Interface Designed To Simulate, Study, And Mitigate Effects Of Interplanetary Communication Delays In Analog Missions* (Publication No. 31336433) [Doctoral dissertation, University of North Dakota]. ProQuest Dissertations Thesis Global.