Enabling Communication Between Astronauts and Ground Teams for Space Exploration Missions

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Abstract— **Over the last four years, Playbook's Mission Log has evolved to become an enabling capability for analog missions that simulate deep space, exploration missions with communication transmission latency. Playbook is a planning and execution web-application for mission operations, aggregating multiple sources of information for astronauts to execute the mission in one place: timeline, procedures, chat interface. Playbook's Mission Log provides a multimedia chat software interface with unique features and functionalities that support asynchronous communication between analog astronauts and ground support teams. This paper describes the iterative design the Mission Log has undergone based on user observations and solicited feedback. Key features include indicators that help users cope with asynchronous communication as well as aids that assist teams coordinate work. Future work and capabilities are outlined, which build upon the increased use of the Mission Log as a communication and coordination tool for space exploration.**

TABLE OF CONTENTS

1. INTRODUCTION

Communications between astronauts and ground teams has always been an essential capability for human spaceflight operations [1]. In general, space-to-ground communication is used to exchange information and maintain shared situation awareness between distributed team members. Voice communications allows astronauts to verbalize current state of spaceflight operations and ask clarifying questions to ground team members. In turn, Mission Control Center (MCC) flight controllers can respond, provide support, and request additional details from astronauts. As such, current spaceflight operation attempts to almost always have voice communication capabilities available with the International Space Station (ISS) when astronauts are awake or are conducting safety-critical tasks (such as extravehicular activities, EVAs, or visiting vehicle docking events).

To date, communication transmission latency between astronauts and MCC has been at most a couple of seconds, as human space exploration has been limited as far as the Moon. However, long distance, long duration exploration missions will impose longer communications latencies between astronaut and Earth-bound flight controllers supporting spaceflight operations. On the way to Mars, space-to-ground communication latencies will increase, and while on the planetary surface, latencies range from 4 to 24 minutes depending on the position of the planets. These latencies are known to disrupt spaceflight communication [2, 3].

In preparation for future exploration missions, NASA has been studying the detrimental effects of communication latency on spaceflight operation and how best to mitigate them through research and Earth analog missions. One of the main outcomes from these investigations has been that as latencies get longer, analog space-to-ground asynchronous communications use and prefer text chatting [7, 10]. The collective experience of these analog missions has consistently reported as a lesson learned the need for communication tools that support not just voice, but other communication enablers such as text, video, history &

playback functionalities, and audio alerts [3,4]. More specifically, exchanging images between space and ground was identified as an essential or enabling capability for collaborating under Mars-like communication latencies [9]. Other researchers have similarly advocated for technological solutions [5] and easy-to-use “information sharing technologies” in support of space mission operations [6].

As part of the Earth analog missions, our team has been supporting mission control by providing an integrated timeline and operations software tool called Playbook [11, 12]. The main function of Playbook is to visualize the shared mission Timeline view, which can be modified by the analog team, and concurrently support texts and file exchange between mission control and analog astronauts with a view called the Mission Log. As many of these analog missions simulate varied amounts of space-to-ground communication latencies, Playbook must also dynamically adjust to the required simulated latencies. Thus, Playbook changes (e.g., timeline modifications or messages) done by analog astronauts are not seen by mission control until the required time delay expires, and vice versa. Two Playbook servers are used to simulate the latency, one for crew and another for MCC, and each holds each change until the transmission delay expires and then sends it to the opposite server. Over the years, Playbook’s Mission Log has become the main platform to exchange text and multimedia files between analog team members. This paper describes the unique challenges that emerge from asynchronous communications and our design solutions to mitigate the detrimental effects of communication latency on spaceflight operations.

2. EVOLUTION OF THE MISSION LOG

The Mission Log originally began as simply a way for analog mission users to post notes, photos, and documents on the mission. The functionality and model was “message post” driven rather than the bidirectional chat communication tool that it is today. Common message types were mission announcements and crew comments. The transition into a chat communication tool embedded into the Playbook product began when the tool was adapted to support simulated communication time delay. The first Playbook simulated communication latency was on the NASA Extreme Environment Mission Operations (NEEMO) 18 analog mission. Mission analogs (like NEEMO) have simulated communication time delay for Mars and Moon contexts, however the tools and technology limited the realism of this simulation. At the time, MCC or the crew manually delayed messages either by receiving an email or using another tool and then starting a countdown timer before reading the message. This was not ideal as many email tools provide a short preview of the contents of the message prior to opening it and the receiving user was already primed that there was a message waiting to be read.

With the addition of transmission delay between MCC and crew, there was value in adapting the Mission Log feature into a chat communication tool. Originally three main features were identified as needed for the adaptation: 1) notifications - the ability to alert a user that a new message arrived, 2) delivery receipts - indications to the user their message was sent and delivered, and 3) countdown timer - indicators how much time was remaining before a message was delivered across the communication delay. While notifications and delivery receipts are common in chat tools, the countdown timer is a unique feature not seen in conventional communication tools and was seen as necessary to support asynchronous communication. After these features were developed, the Mission Log became heavily used in analog mission as a communication tool both for the real time and communication delayed contexts. As a result, the Mission Log has been used as a chat communication tool in multiple analog missions over the last four years: NEEMO, Pavilion Lake Research Project (PLRP), Biologic Analog Science Associated with Lava Terrains (BASALT), and Human Exploration Research Analog (HERA).

Over the subsequent analog missions, additional features were incorporated into the Mission Log based on our team’s observations of operations and user feedback from both analog crew and MCC. Among these features are labeling high priority messages and acknowledgements. These are further described in this paper. Through these iterations in various analog missions, the Mission Log has evolved from a note-taking software into an embedded communication tool that supports the unique needs of future spaceflight missions.

3. MISSION LOG OVERVIEW

The Mission Log has an interface very similar to most modern text and multimedia-based chatting software. Figure 1 shows a screenshot; the upper quarter of the user interface is dedicated to composing and sending messages, while the lower part is dedicated to viewing a running log of all messages going between MCC and crew. The user is expected to select their icon (e.g., Figure 1 has crew icons as EV1, EV2, IV1, and IV2 while ground control has ST and MCC icons[1]) and then compose their message in the text box. The Mission Log supports multiple languages, GIF animations, and emojis. Playbook currently does not require individual account logins, which allows for each crewmember and MCC to view all messages at all times, which increases situation awareness across team. Once a message is drafted, the user can identify the message as high priority. The high priority checkbox allows users to send messages of elevated importance. Additionally, the user can attach a file, including photos and videos, which appear in-line.

[1] EV1 and EV2 refer to astronauts conducting Extravehicular activities outside the habitat, while IV1 and IV2 refer to Intravehicular astronauts managing an EVA from within the habitat. ST is Science Team back on Earth.

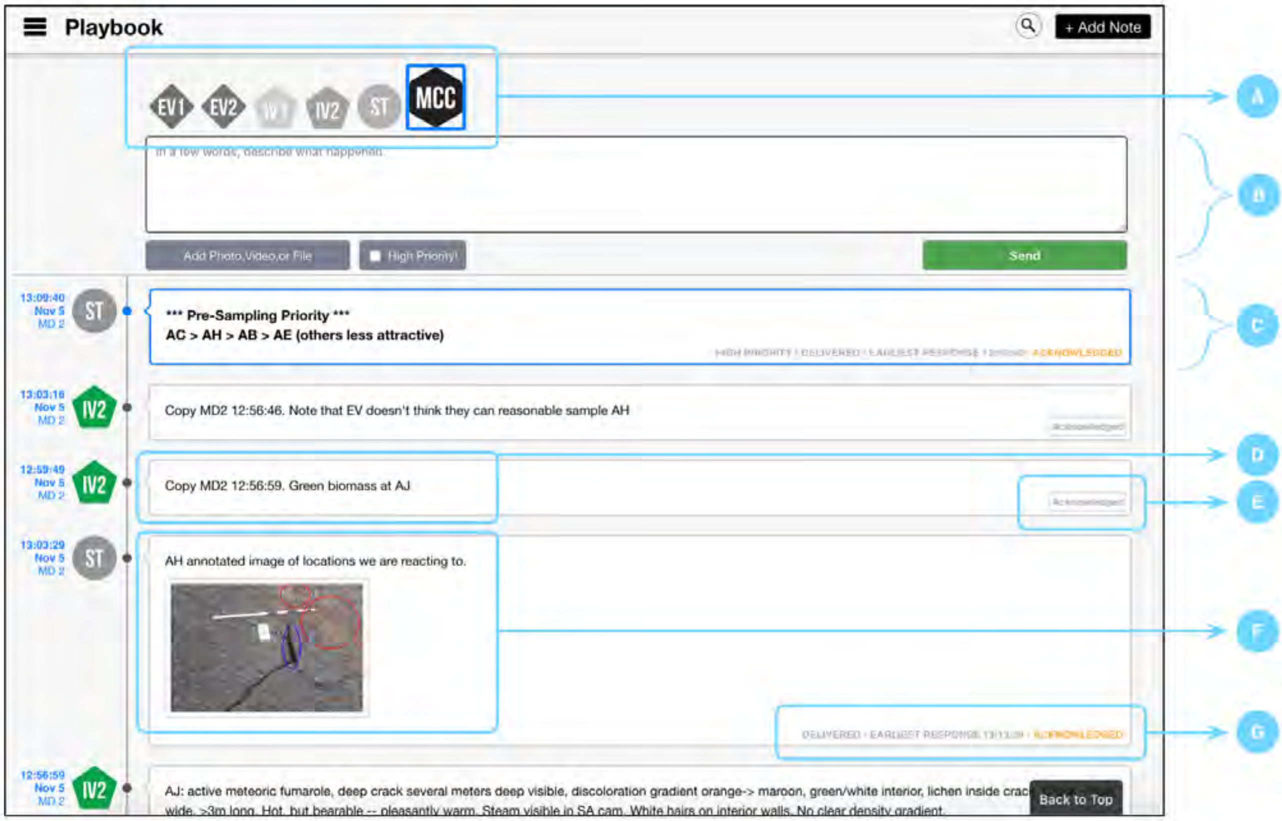

Figure 1: Playbook's Mission Log overview. (A) "From" icons; (B) free form text box, attachment link, and "High Priority" flag; (C) "High Priority" message; (D) "Copy" text and link; (E) "Acknowledge" button; (F) Imbedded attached image file; and (G) Timers and "Acknowledged" state.

Once sent, the message is time stamped and appears in the sender's log. After the expected communication transmission delay, the message becomes visible to the receivers in the log section as well. Each message also has countdown timers and indicators to acknowledge receipt of message. When a message is received, a tone sound is emitted (a quindar tone[2]), alerting all receiving users of the incoming message. All the messages for the analog mission are saved in the log, allowing for users to go review any messages at any time.

4. ASYNCHRONOUS COMMUNICATION CHALLENGES AND COUNTERMEASURES

Texting facilitates asynchronous communications because the message can be received and read without interrupting current work. The Mission Log is used in analog mission for asynchronous communication because off-the-shelf, traditional chat software tools do not simulate transmission delays nor do they provide additional aids to deal with the unique challenges that occur. The most common challenge we have observed teams face is losing track of conversations as replies are delayed. More specifically, team members might miss messages that were part of particular conversations. This is further exacerbated when there are a lot of conversations happening, typically during activities that require a lot of coordination between crew and MCC. As a result, it is possible to lose situation awareness and time may be wasted tracking down responses. We have noticed that with the added time required to wait for responses, team members tend to be descriptive. When each round-trip message costs a significant amount of time, team members want to know not only if the message was received but also understood. Over the last four years, our team has observed analog missions while operating under asynchronous communication and consequently, designed and implemented unique countermeasure features that aid in communicating with transmission latency. We have grouped these features into functions that support latency, high communication rates, visibility into work, and workload.

Cues for Communication Latency

The Mission Log provides multiple cues and indicators that provide insight as to the effect of communication transmission latency (Figure 2). Users are given the following information: 1) timestamp for when message was sent, 2) dynamic countdown timer to when message will be received (i.e., after transmission delay), and 3) a timestamp for the earliest expected response time. The countdown

[2] https://www.hq.nasa.gov/alsj/quindar.html

timer provides a clock timer in each sent message to indicate how much time is remaining before it arrives at the receiver's site (MCC or crew). This capability is helpful and heavily used as users requested more precise timing information; initially, the timer only showed minutes, and based on user feedback, seconds precision was added. It was observed that users do not have an easy way of tracking the effects of communication latency. Users would often wonder why the other person had not replied to their message, not realizing that the delay between crew and MCC had not yet transpired. The earliest expected response time provides that information, essentially calculating the round trip of the one-way latency time.

Aside from aiding users with timing information, the Mission Log also cues the user when a new message has arrived. Notifications of new messages are both visual and auditory. After several iterations, the Mission Log has settled on providing a quindar tone any time a new message arrives from across the transmission latency, as a visual cue was not sufficient to alert teams of incoming messages. The quindar tone was selected because it is reminiscent of Apollo communication protocols. Both the message notifications and time cues have become essential features in supporting asynchronous communications.

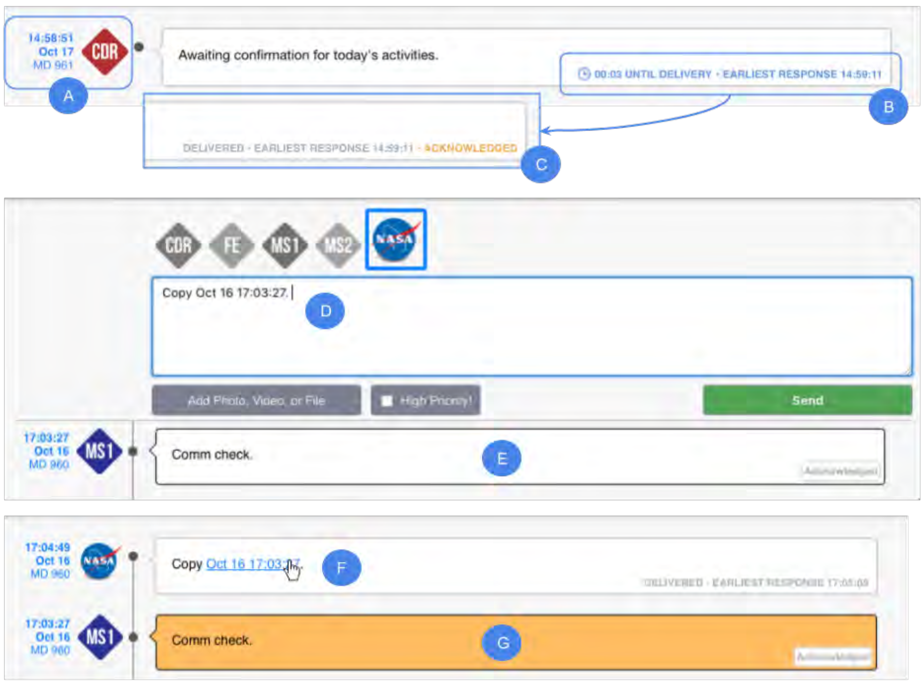

Figure 2: (A) Message's sent timestamp, (B) Countdown timer for message to be delivered and earliest response time, (C) Message's indicator of delivery, earliest response time, and acknowledgement indicator, (D) Automatic "Copy" text from (E) message selected, (F) Message's link to response message, (G) highlighted in yellow.

Reducing Workload

One of the main responsibilities of analog mission team members is to cooperate and coordinate work, yet communications should not be a task that significantly adds to workload. We observed that two particular tasks that were cumbersome to users: repeated "Copy" replies and finding previous posts. During verbal conversations, it is easy to acknowledge that your communication was received with "Copy". "Copy" messages reassure the receiver that their message has been seen and understood. We observed that users would reply to a previous message by starting a new message with "Copy {hh:mm}, … " followed by text, where {hh:mm} is the timestamp of the original message. This required both the sender and the receiver the cumbersome task of scanning the Mission Log for the message with that timestamp. In response to this usage, we developed a feature to recognize timestamps in messages and create an automatic link to the message with the associated timestamp. Users can hover over the link of the timestamp and the message with the corresponding timestamp gets highlighted; clicking the timestamp link will scroll to the message. In addition, if a user selects a previous message and simultaneously creates a new message, the new message will auto-populate "Copy {hh:mm}." for the timestamp of the selected message, creating a thread of communication through these timestamp links (Figure 2, areas "D" and "F").

Finding previous messages became cumbersome when a large number of messages were posted in the Mission Log. A Search capability was designed and developed. Our design allows users to see Search results in a tray alongside the entirety of the Mission Log (Figure 3). Clicking on a message on the Search tray will scroll to it in the Mission Log, highlighting the message and allowing users to see the message in the context with the rest of the conversation as well as temporarily highlighting it for ease of finding. Once this functionality was in place, users started using the Search tray to change the way they scanned messages. By adding key terms to the Search tray, the results filter the messages that match the terms. During a couple of analog mission deployments, the Science Team on Mission Control agreed to use a predetermined set of headers in messages to help them identify messages that contained specific content (akin to an email's subject line). The crew used these headers in the Search tray in order to keep all of those messages in the Search tray and it would served as a filtered Mission Log. Whenever new important science messages came in, they would show up at the top of the Search tray, reducing the likelihood of being lost in the Mission Log stream. This technique could similarly be used for conversations related to particular experiments if the analog mission agreed on experiment tags. The Search tray would filter the Mission Log for relevant, current experiment information in the context of other messages.

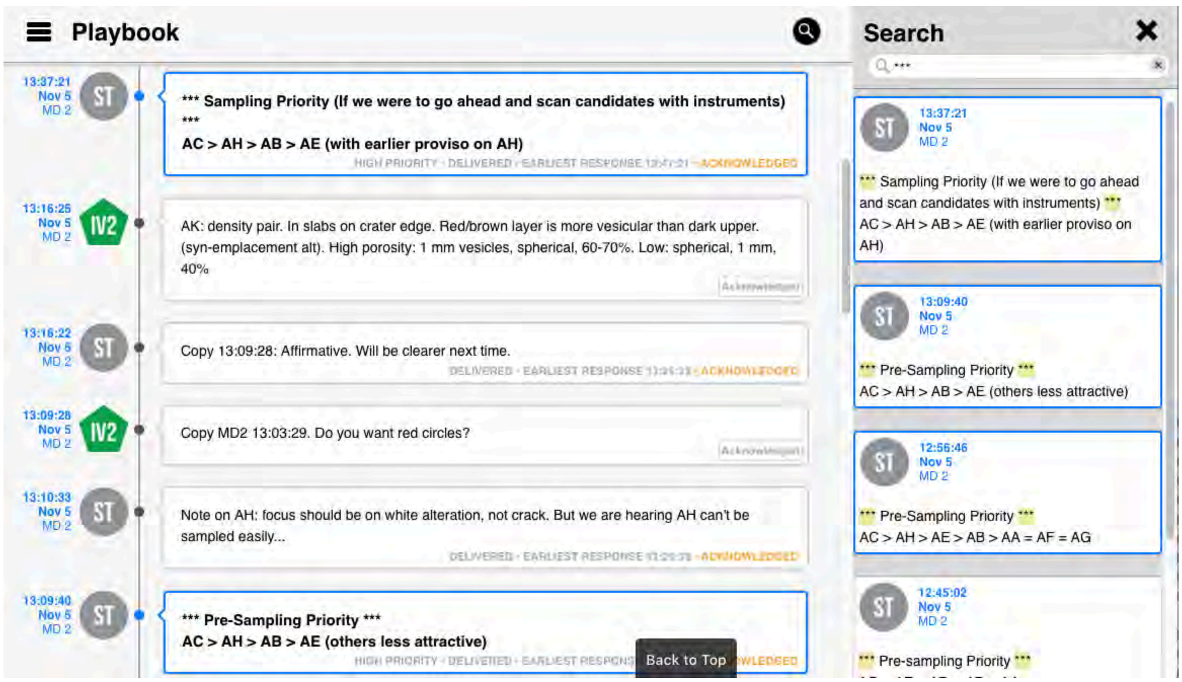

Figure 3: Mission Log messages on the left, alongside the Search tray on the right with key term filtering messages in tray.

Managing High Communication Rate Exchange

As mentioned, transmission delay results in ambiguity with regards to messages being received. While the cues for communication latency aid in reducing this ambiguity, high communication rates exacerbate this problem. To date, we have designed and implemented three main features that help users manage their conservations during periods of high message exchange: 1) as-received message ordering, 2) high priority messaging, and 3) acknowledgments.

Initially, the Mission Log ordered messages the same way off-the-shelf chat software orders messages, in the "as sent" order. Therefore the log had messages ordered by their sent timestamp, i.e., chronological order. At first, this ordering worked, as Mission Log use was limited. With a small number of messages going between crew and MCC, both sides could easily follow the flow of the conversation contained in the messages. However, as the Mission Log's role increased in more complex missions, the rate of messages being sent between MCC and crew increased greatly. When there were multiple conversations happening in the Mission Log at the same time, users started reporting that they would miss messages because the "as sent" ordering meant some messages would appear below newer messages sent from their side. This unique usability challenge, which off-the-shelf chat software would not encounter, emerged because of the communication latency of analog missions. This usability issue was resolved by changing the Mission Log's message order to be "as received" instead. As a result, crew and MCC always saw incoming messages at the top.

With high communication rates, messages can sometimes be missed due to the volume and rate of messages being sent. As the number of messages accumulates, the log would get longer, no longer visible in the screen (i.e., only viewable to users if they scrolled down the log). Furthermore, it was observed, and user feedback indicated, that important, critical messages could be missed. (This was also exacerbated due to the "as sent" ordering.) In the context of spaceflight operations, missing critical messages is not acceptable. Keeping track of the most relevant messages became difficult. Because of these observed issues, we developed a feature to mark messages as high priority messages and made them salient in the Mission Log interface (Figure 1, area "C"). These high priority messages are designed to stand out and capture the user's attention with differentiated styling and also "float" above all other messages for a limited amount of time. In addition, the text is bolded and the post itself has a thick blue outline, visually differentiating it from other messages.

During periods of high communication exchange, it was observed that many of the messages were simply "Copy" messages. Using this feature for every message resulted in visual clutter due to the high quantity of back and forth of messages that only had a "Copy" message. In order to minimize the number of "Copy" messages and decrease the clutter, an "Acknowledge" feature was developed. An "Acknowledge" button was added to the right of each message; the receiver would then click on it to acknowledge received message. In turn, the sender sees an indicator in the message that it has been received and acknowledged (Figure 1, areas "E" and "G', Figure 2, area "C"). The ordering of messages, high priority messages, and acknowledgments has helped users manage high communication rates, though additional improvements are still warranted (as discussed in User Feedback and Remaining Challenges).

Visibility into Work

The Mission Log supports sending messages with attachments such as documents, photos and videos, consistent with most chatting software tools. This has been shown to be an invaluable functionality. Since Playbook is designed to work on mobile devices like iPads, one emergent use of attachments is that users can quickly use the camera in their mobile device to take a photo or video and share it through the Mission Log. This functionality has been popular, likely due to the low effort involved as compared to ISS operations. As described by flight controllers, sending a photo or video from the ISS to the ground is currently not a straightforward process. Astronauts have to take photos with a camera, import the photo or video to a computer, place them in a folder specified by Mission Control and wait for a downlink for the ground controllers to receive, which is a lengthy process. With the Mission Log, this process is streamlined, potentially enhancing communications by avoiding time-consuming context-switching and workflow breakdowns.

Being able to share these media resources can reduce verbal or text descriptions. We have observed in various analog missions that crew have consistently used photos or short videos to help the ground team diagnose unexpected errors or behaviors in equipment. We also have observed that sharing media easily is not only beneficial for when things go wrong, but also during the execution of complex experiments. For instance, the crew can send photos at specific checkpoints of the procedure through the Mission Log without significantly disrupting their workflow, allowing the experts on the ground to monitor the execution of procedures and can provide adjustments or suggestions, potentially getting ahead of the effect of compounding time latencies. In some analog missions, ground-based science teams have sent crew annotated images to help them conduct simulated EVAs, providing more precise guidance for task execution.

In addition to being able to post messages in the Mission Log, users can also send messages from the Timeline view (Figure 4). This allows users to send a message without moving away from the Timeline context. The user clicks "Add Note" in the Timeline, creates a message (which is also posted in the Mission Log), and a marker pin is viewable by everyone in the Timeline. These messages can be associated with an activity or a specific time. (Additional messages can be added through the Activity's Details [11]). If an activity has a Note associated with it, a marker pin indicator appears on the activity. Users can click on the Note pin and read the note without moving away from the Timeline view (Figure 4). This feature better integrates data between the Mission Log and the Timeline.

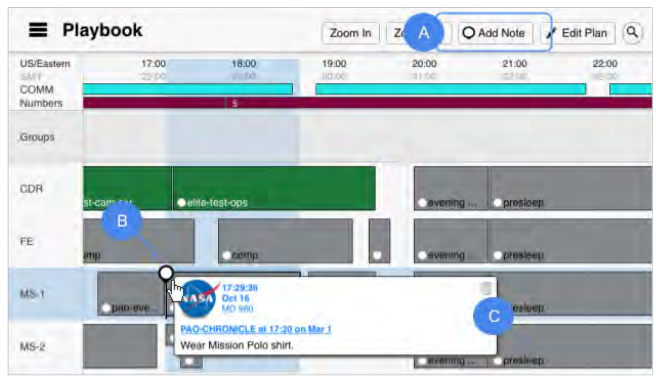

Figure 4: (A) "Add Note" in Timeline to create a Mission Log message associated with (B) an activity with an indicator. (C) Message can be viewed in the Timeline.

5. User Feedback and Remaining Challenges

Over the last four years, we have requested subjective user feedback about Playbook from analog crewmembers and mission control personnel. These users were asked to identify three things they liked and three improvements they would like to see in Playbook. Improvements for Playbook's Mission Log have been submitted since its creation in 2014 (Figure 5). Many of the features described in this paper are based on the collective requests from users: message search, acknowledgments, high priority messages, and message timers. As the Mission Log improvements were implemented, the relative number of the Mission Log requests has decreased, suggesting that it has become a more usable and effective aid over time.

Despite the relatively large requests for improvements, just over half of users had one or more positive comments attributable to the Mission Log:

- *"Really liked utilizing the Mission Log .. very useful"*
- *"[Mission Log] Enabled me to better manage my*

time and attention during high intensity periods"*

- *"[Mission Log] served as a good record for information we might want to look at later on"*
- *"It was so much easier to send and receive messages with the science backroom team via Playbook than voice"*

The rest of the comments identified specific Mission Log features users liked (Figure 6). The feature that users mentioned the most was the ability to communicate quickly to other crew and MCC through text alongside a history of past messages. Users also mentioned the cues for communication latency (e.g., counters, quindar) as being crucial to managing communication between the crew and MCC. The Mission Log's clear presentation and ease of use was also highlighted, users pointed specifically to features like the high priority messages and the search capabilities visual design and usability. Based on user feedback, we also ascertained that attachments of photos and videos were an effective way to communicate complex ideas across the team. These results support the need and desire for not only a multimedia text-messaging tool but also one that is customized to provide additional aids for users while communicating asynchronously.

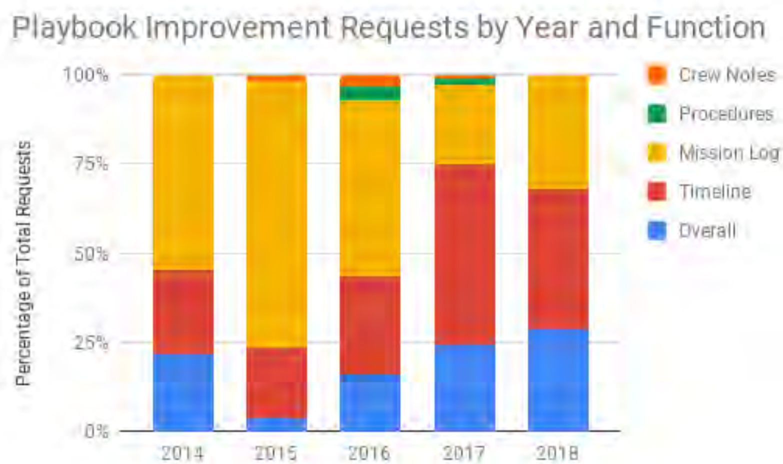

Figure 5: Percentage of total improvement requests related to the various components of Playbook

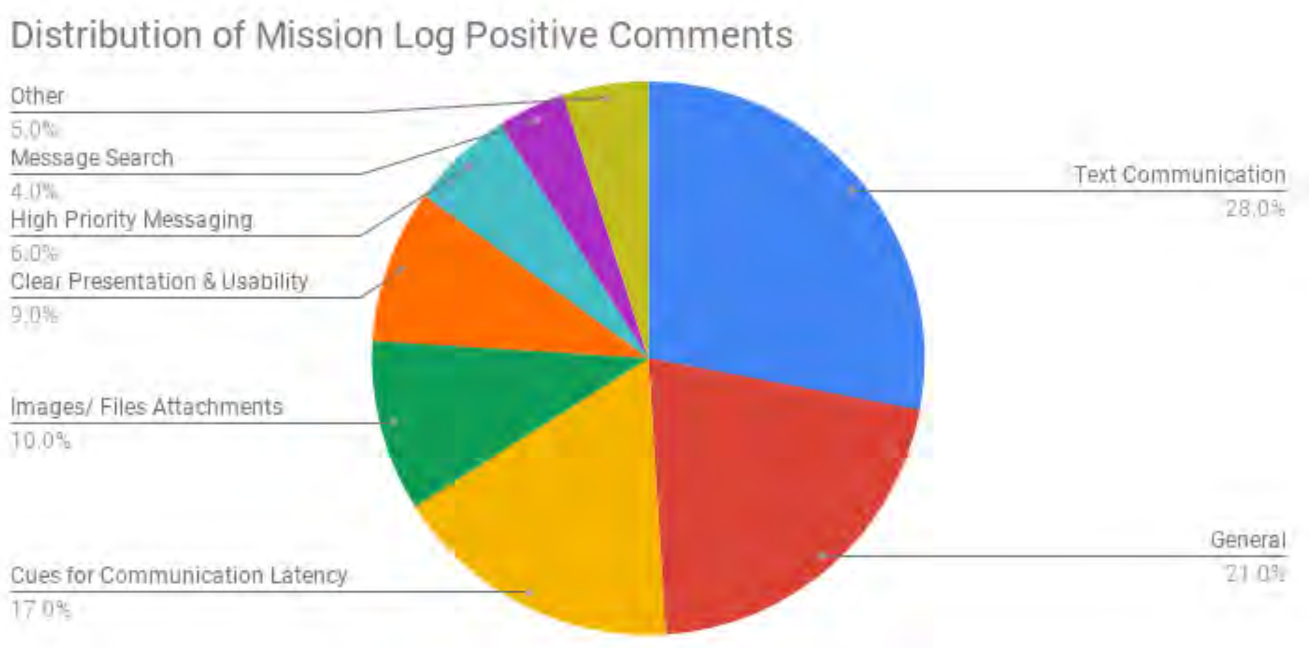

Figure 6: Distribution of types of positive comments associated with the Mission Log

Future Mission Log work will focus on implementing additional key features identified as supporting asynchronous communication and coordination. With regards to communication, a frequent request is the inclusion of message threads, i.e., grouping of messages based on conversation or topic. This is particularly relevant when there are multiple threads in the same "channel" of communication or if there is high volume of messages and users are trying to find responses to their previous questions. Similarly, there are requests to filter messages based on a relevant parameter (e.g., topic or by-sender). Some users would also like to specify the message's recipient and/or make those messages private. Additionally, message senders would like to know not only that their message was received and read, but also who acknowledged it. Since everyone is using the same "channel" and the lack of immediate confirmation, specifying who did each communication action ("from", "to", "received by") is highly desired. Users would also like to make more complex messages: include multiple image attachments, write messages in rich text (e.g., bold, colors, tables, bullets), add customized message headers, and integrate voice communication into the log (either attach voice notes or transcribe voice notes into the Mission Log). Recently, MCC users recommended a message "draft" feature, where they could draft and review messages with the ground team before sending them to crew. Finally, better accessibility in smaller form-factor platforms (i.e., phone) has been requested as well.

One of the most interesting developments in the last couple of years has been the evolution of how the crew uses the Mission Log as a form of "to-do" list to coordinate asynchronous work. While operating with communication latency, messages from MCC to crew request follow up actions. Crew currently have the ability to identify the message as received (through "acknowledge" checkbox) yet they want to continue tracking this message as an action to complete and then let MCC know it is done. To that effect, crew has requested being able to keep their own list of messages -- "favoriting" them or identifying them as "high priority" to them. Additionally, a couple of users have requested for tasks reminders (or alarms) to be posted on the Mission Log.

Further integration of the Mission Log and Timeline has also been suggested as an improvement. The Mission Log has been heavily used to coordinate science tasks, where crew collect specific samples guided by science team, located in MCC. Occasionally, the crew is left wondering how up-to-date MCC was when they sent a message. For instance, crew might ask themselves "did MCC see this new information when they sent this set of priorities?" While technically possible, the user could cross correlate the timestamp of when the message was sent with a time in the schedule. However, under time-pressured circumstances, this is not easily done. Thus, crew could benefit from seeing all Mission Log messages in a similar manner to Timeline Notes.

6. CONCLUDING REMARKS

Over the course of several years, we have observed, designed, and implemented multimedia chat software that enables analog mission operations under communication latency. Though still in development, we have observed Playbook's Mission Log become an essential communication tool in the analogs. The Mission Log has unique capabilities not currently found in off-the-shelf chat software that supports asynchronous communications. Future work will focus on better supporting higher volume of messages, multiple conversations, customizable messaging, and to continue enhancing integration between Timeline and Mission Log for task coordination.

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BIOGRAPHY

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Steven Hillenius *leads the Playbook/SPIFe team at NASA Ames Research Center. As part of his work as a Principal Investigator for an HRP research proposal on onboard planning he has led the design and development of Playbook from a plan viewer into a crew autonomy tool. Previously he did product design and conducted user research for Score, MSLICE, and LASS, a series of SPIFe mission planning tools used for International Space Station crew planning, Mars Science Laboratory (Curiosity) rover planning, and LADEE (Lunar Atmospheric Dust Environment Explorer) orbiter planning. Steve holds a Masters in Human-Computer Interaction and a B.S. in Information Systems with an additional major in Human-Computer Interaction, both from Carnegie Mellon University.*

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