CHAPTER 36

TEAMWORK IN SPACEFLIGHT OPERATIONS

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Apollo 13: An Example of Teamwork in Spaceflight Operations

"Houston, we've had a problem" (Test Division Apollo Spacecraft Program Office, 1970, p. 160). This now famous statement by Jim Lovell, the Commander of Apollo 13, marked the beginning of an extraordinary rescue mission. Apollo 13 was 200,000 miles away from Earth when an oxygen tank in the spacecraft's service module exploded, resulting in the depletion of the crew's supply of electricity, light, water, and oxygen.

To get the Apollo 13 crew back home safely required much individual expertise and ingenuity, but above all, it required exceptional teamwork both within mission control and between flight controllers and the crew.

Gene Kranz, the lead Flight Director for Apollo 13, orchestrated the rescue effort. He and his team of flight controllers were working the shift in the Mission Control Center at Johnson Space Center when Lovell's message came in. Updates from the crew—meter readings and warning light indications—and system reports from flight controllers presented a confusing picture. "Everything we knew about our spacecraft," Kranz recalls, "all that we had learned about the design, precluded the kind of massive failure we were seeing" (Kranz, 2000, p. 313). While flight controllers dedicated to the craft's life support systems assisted the space crew in their troubleshooting, others backed them up and eased their workload. For instance, they monitored the signal strengths of the craft's antennas and kept track of the craft's attitude, and when critical changes occurred, they called for appropriate crew action to ensure uninterrupted communication and usable readings from the craft's gyroscope. Mission control's centralized decision making and communication ensured an orderly interaction with the crew (Vessey, 2014). Flight controllers made their recommendations on crew actions to the flight director who, insofar as he agreed, had the Capsule Communicator (CAPCOM), an astronaut, relay the instructions to the crew.

Fifteen minutes into the crisis, the nature and scope of the problem became clear at last when Lovell reported that the craft was "venting something out (. . .) into space. It's a gas of some sort" (Kranz, 2000, p. 163). At that moment, it became apparent that an explosion in the service module had destroyed the space craft's cryogenics and fuel cells, and that the mission had become one of survival (Lovell, 1975). As the oxygen supply in the spacecraft's command module kept decreasing, crew and mission control agreed to move the crew into the lunar module and to use it to propel the command/service module so that its remaining resources could be saved for reentry. The next major question mission control faced was how to bring Apollo 13 back to Earth. Kranz and Glynn Lunney, his flight director colleague, worried that an immediate abort would curtail their options, given they didn't know whether the craft's main engine had been damaged in the explosion. They wanted more time to plan for reentry and thus favored the long way around the Moon. Confident that mission control and crew had the expertise to solve resource limitations on the spacecraft, they made the case for this option in discussions with other flight directors and the chief of flight operations, Chris Kraft, who ultimately agreed. Kranz then handed over command to the other flight directors and their teams of flight controllers to man mission control around the clock while he and his team went to work on detailing the return procedures for Apollo 13. Several issues had to be planned for—maneuver procedures to speed up the return; an integrated checklist for the reentry phase; use of spacecraft resources; management of lunar module resources; and a master plan to lay out the steps required for reentry and their timing. Subteams of flight controllers together with astronauts and engineers worked out solutions and tested them in simulations, all over the course of three days. On April 17, 1970 at 1:08 p.m. CT Apollo 13 splashed down successfully in the Pacific. As Kranz (2000) recounts: "Our crew was home. We—crew, contractors, controllers—had done the impossible. The human factor had carried the day" (p. 337).

Spaceflight operations—thankfully—tend not to be as dramatic as Apollo 13. Nonetheless, even though it is an extreme example, Apollo 13 brings to the fore the central role teamwork plays in any space mission. While the success of space missions unquestionably depends on the technical expertise of individuals—of astronauts and mission controllers alike—their complexity requires superior teamwork as well. In this chapter, we will show that teamwork in spaceflight operations is a multiteam effort requiring the coordination and collaboration not only of individuals within a team (mission control or space crew) but importantly also between the teams. We will discuss the strategies and procedures these expert teams have established to ensure common task and team models, as well as to facilitate their communication and joint performance. We also will address the teamwork challenges of future space exploration, and we will describe efforts to mitigate these problems. Our chapter begins with a discussion of the teams (mission control and space crew) that make up the multiteam system, highlighting important features of their (intra)teamwork. In the final section, we raise questions and methodological issues that research will need to address to support the collaboration between space crews and mission control during future long-duration exploration missions.

Mission Control and Space Crew as a Multiteam System

Conducting space missions is a complex task. Knowledge and expertise are distributed across co-located and remote team members so that communication and collaboration among not only individuals but also teams of experts—the crew in space and flight controllers on the ground in mission control—are essential to successful performance. This form of teamwork has been characterized as a multiteam system (MTS; Mathieu, Marks, & Zaccaro, 2001) to emphasize the interdependencies that exist between component teams.

As part of a multiteam system, crew and mission control rely on each other for information and resources. They cannot complete their respective tasks without successful task performance by the other team, and mission goals are achieved through a concerted effort. This interdependence between the teams is most visible during extravehicular activities (EVAs) when one or two crewmembers are outside their spacecraft to conduct specific tasks, such as maintenance or repair work. This situation is depicted in Figure 1 with the right-hand panel showing two crewmembers as they perform a maintenance EVA on the International Space Station; the left-hand panel captures the concurrent activities in the Mission Control Center (MCC) at the Johnson

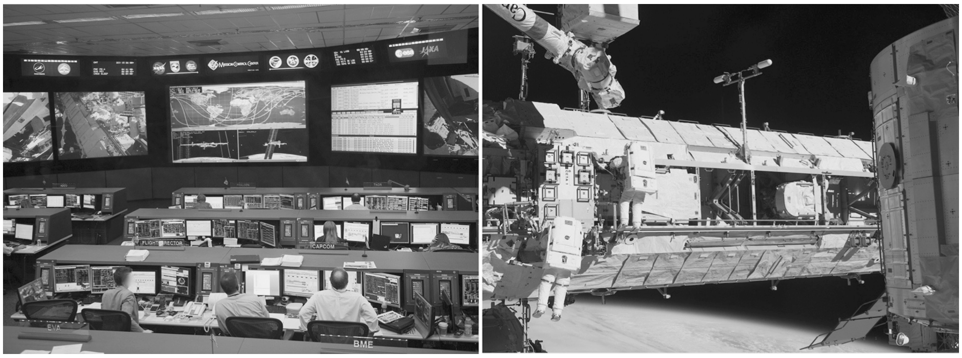

FIGURE 1 (Left) An overview of the flight control room in the Johnson Space Center's Mission Control Center (MCC) as flight controllers support extravehicular activity (EVA) by astronauts on the International Space Station (ISS). (Right) Two astronauts during an EVA conducting maintenance activities outside the ISS.

Images courtesy of NASA.

Space Center in Houston, Texas. During an EVA, controllers in MCC fulfill critical monitoring and managing functions (Miller, 2017). EVA ground personnel monitor the performance of the EV (extravehicular) crewmembers and keep track of the task timeline. They watch the crew's limited consumables (e.g., O_2, CO_2, etc.), assess their health, and ensure that the communication and power systems supporting the EV crew are configured accurately and are functioning properly. One dedicated position, the EVA flight controller, leads and coordinates all EVA activities in MCC while communication from MCC with the EV crew is channeled through the ground intravehicular operator (ground IV) who assists the EV crew with procedures and checklists and relays timeline changes to them.

Missions to the International Space Station add an additional layer of complexity to the MCC/space crew multiteam system insofar as they are carried out jointly by teams from different space agencies residing in different countries (e.g., NASA in the USA, Roscosmos in Russia, the European Space Agency with centers across Europe, and JAXTA in Japan). In this chapter, we will focus exclusively on the US multiteam system consisting of NASA astronauts and NASA mission control. Before we discuss teamwork as it relates to the MCC/space crew multiteam system, we need to take a closer look at team processes in its component teams.

Teamwork in the Mission Control Center

The current focus of MCC operations at NASA Johnson Space Center is on missions to the International Space Station (ISS). Flight controllers in MCC are trained to become experts in specific ISS systems (e.g., power and communication systems; Vessey, 2014). They must learn not only how that system functions and how to troubleshoot it, but also the impact that abnormalities or malfunctions will have on other systems on the ISS. Additionally, they train to pool their expertise effectively with other flight controllers. For example, a flight controller may be assigned to work in a *backroom* during off-nominal events to support the frontroom controllers and highly experienced system specialists who have complementary expertise (Kranz, 2000). This operational setup, which has been characterized as distributed supervisory coordination (Caldwell, 2001; 2005), means that subject-matter expertise within and across ISS systems is distributed among several flight controllers in two different locations (frontroom and backroom), and requires complex coordination and collaboration among these experts. Other team members in MCC include the flight director, who is the formal leader and decision maker in MCC, and the CAPCOM, who manages communications between MCC and the astronauts (Vessey, 2014).

In addition to subject-matter expertise, flight controllers exhibit the other five dimensions of expertise described by Garrett, Caldwell, Harris, and Gonzalez (2009; see also Onken & Caldwell, 2011): situational context expertise, or the ability to assess a situation by gathering information and to know how the situation impacts goals; expert identification expertise, related to transactive memory (DeChurch & Mesmer-Magnus, 2010), or the awareness of who knows what and when to ask for data or information from them; communication expertise, or the ability to communicate clearly with team members; and two dimensions of expertise around the technology used in MCC—interface tools and information-flow path. These dimensions come into play during different operational events and phases of events. For example, detection of an anomaly may be guided by a controller's subject-matter expertise; in contrast, isolation of that anomaly and creating a hypothesis about its cause requires teamwork among controllers and may involve all dimensions of expertise (Onken & Caldwell, 2011).

MCC expertise is honed using complex high-fidelity simulations that emulate events and configurations found in actual missions. This enables extensive practice on both frequently occurring tasks and low-occurrence events such as system malfunctions. Effective MCC task coordination depends on the quality of team members' taskwork (i.e., actions directly related to accomplishing their assigned task), teamwork (i.e., behavior in support of their collaboration), and pathwork (i.e., capabilities concerned with the flow of essential computer and vehicle sensor data). Both taskwork and teamwork entail extensive knowledge sharing, and challenges for particular situational contexts (operations, problems, failures) include knowing what information to share, and how and when information should be shared or requested—for example, when to call upon the knowledge of backroom specialists (Caldwell, 2005).

A variety of methods (observation, critical incident interview, and operator feedback) and contexts (live shuttle operations, ISS missions, and training simulations) have been used to understand team coordination in mission control (for reviews of these and other methods, see Section II, "Methods to Study, Test, Analyze, and Represent Expertise," this volume). Research has focused on how information is shared and how actions are coordinated across consoles—i.e., between flight controllers with different technical expertise and responsibilities—and between the front- and backroom flight controllers who share the same technical expertise.

Fiore, Wiltshire, Oglesby, O'Keefe, and Salas (2014), for example, conducted semi-structured critical incident interviews to investigate MCC problem-solving processes around a complex problem—the failure of the ISS main bus switching unit. This particular problem requires MCC team collaboration so that relevant data are identified and pooled and MCC team members come to a shared problem model, and generate and execute solutions. The goals of this naturalistic study were to identify the team processes involved in collaborative problem solving by MCC team members and to determine whether they were consistent with the Macrocognition in Teams Model (Fiore, Smith-Jentsch, Salas, Warner, & Letsky, 2010). The analysis of the interview data revealed that as predicted by the model, most of the behaviors mentioned reflected efforts by these experts to build a common knowledge base and a shared problem model. In so doing they drew on position-specific knowledge of individual controllers as well as relied on shared domain knowledge. Specifically, MCC team members were sensitive to the time constraints of their teammates and recognized when to disseminate information to others, how to transform information into *actionable knowledge*, and when to consult subject-matter experts for relevant system knowledge.

Mission control requires the integration of multiple data points into meaningful patterns and involves continuous tasks (e.g., monitoring a system malfunction) as well as long-term plans that have to be carried out across multiple shifts, possibly until the end of a mission. Patterson and Woods (2001) conducted field observations to understand the processes involved in handovers between outgoing and incoming MCC personnel. When mission controllers change work shifts, the handoff meetings are initiated by incoming controllers and conducted in an interactive fashion. Incoming personnel gather information on current mission events or significant occurrences in the recent past prior to their meeting with their outgoing counterparts (Patterson & Woods, 2001). They look through relevant documents, such as the flight log, and join their outgoing colleagues at their console, viewing the monitors and listening to ongoing communications. These actions serve several purposes. Incoming controllers develop an understanding of the task environment, its current status, how it evolved, and how it might develop. Their interpretations likely facilitate interactions with their outgoing colleagues because aspects of the task environment can be presumed to be shared knowledge and to require no further discussion. Handoff meetings can thus focus on verifying the accuracy of the incoming controller's situation model and on providing additional detail (Durso, Crutchfield, & Harvey, 2007), and as a result promote a collaborative review and check (Patterson & Woods, 2001). That is, incoming controllers' interpretations and expectations may serve as a check on outgoing controllers' assumptions regarding a situation so that errors are identified and prevented from escalating into problems (Patterson & Woods, 2001).

The interactive nature of their discussion provides controllers with the opportunity to detect and correct knowledge gaps or misconceptions concerning mission-critical aspects, to remind one another of important issues, and to build shared mental models of the task environment, including off-nominal events and their implications, as well as plans and their associated assumptions. Handoffs between incoming and outgoing controllers do not follow a predefined script and rely on everyday conversational norms. To ensure the completeness and accuracy of these briefings and to coordinate activities with other controllers on the shift, a cross-checking process is invoked: incoming backroom controllers brief incoming frontroom controllers via a public voice loop communication system on the content of their individual handoff meetings with the colleagues they are replacing (Patterson & Woods, 2001).

In addition to direct dissemination through handovers, information is indirectly transmitted via voice loop groupware technology. This technology facilitates MCC teamwork by enabling flight controllers not only to communicate with other people in MCC, but also to monitor the conversations and activities of others—thus enhancing their situation awareness and providing the opportunity to detect instances that do not match their expectations, deviations, errors, or omissions on tasks (Caldwell, 2005; Patterson, Watts-Perotti, & Woods, 1999). An important facet of controller expertise is the ability to remain peripherally attentive to these voice loops and to shift attention to a communication channel when appropriate, for instance when something is discussed that will have a direct impact on the controller's subsystem. Not surprisingly, the Flight Director's channel has been found during simulated training missions to have higher utilization across missions and phases of missions than other channels, in particular the air–ground and ground controller loops (Wang & Caldwell, 2003).

One of the most important teamwork functions facilitated by voice loops is anticipation. When controllers monitor ongoing activities, they can anticipate events or problems and synchronize communications and actions with other controllers. They are aware of other controllers' workload, can judge their progress, and discern when to interrupt them. Moreover, they can take advantage of other controllers' data transfer as it evolves into integrated, event-level information, enabling them to quickly ascertain the impact of anomalies in systems related to their own subsystem (Patterson et al., 1999).

Teamwork in Space Crews

During the early years of spaceflight crews consisted of two or three astronauts. In current ISS operations, astronauts are members of a multinational team of six. Crewmembers are highly motivated and capable of adapting to stress and changing conditions. They are achievement-oriented, are intelligent, and frequently have an advanced degree in engineering, the biological and physical sciences, or mathematics, and/or professional experience in these fields (Landon, Vessey, & Barrett, 2016; Vessey, 2014). The selection process for astronaut candidates is highly competitive and rigorous and once selected, they will be in training for 5 to 10 years before their first mission. Astronaut training traditionally has emphasized technical expertise but in recent years, training in team skills and cultural competencies has been included partly in response to reports of interpersonal tension and conflict during Mir and ISS missions, and partly in preparation for future long-duration exploration missions.

While crewmembers have a common passion for space exploration and share many personality characteristics, they bring different technical expertise to a mission and thus fulfill different roles. They also have different ranks. One crewmember is the commander who during the flight

> has onboard responsibility for the vehicle, crew, mission success and safety of flight. The pilot assists the commander in controlling and operating the vehicle, and may assist in the mission experiments and payloads and their operations. Mission specialist astronauts work with the commander and the pilot and (. . .) are trained in the details of the orbiter onboard systems, as well as the operational characteristics, mission requirements and objectives, and supporting equipment/systems for each of the experiments conducted on their assigned missions. Mission specialists perform EVAs (extravehicular activity), operate the remote manipulator system, and are responsible for payloads and specific experiment operations.
>
> (Erickson, 2010, p. 281)

The importance of leadership to the cohesion and effectiveness of teams that work under isolated and extreme conditions has been well established in surveys of Antarctic science team members (Wood et al., 2005), crewmembers in space analogs (Kanas, Weiss, & Marmar, 1996) and astronauts during Mir/Shuttle missions (Kanas, 2005; Palinkas, 2001) and on the ISS (Kanas et al., 2006). Surprisingly, Kanas and colleagues (2006) observed that crewmembers' ratings of team cohesion were related only to perceived leader support. There was no significant link between perceptions of a leader's task role and team cohesion. The researchers suggest that this finding may have been a function of the small crew size on these missions. With only three crewmembers who had specialized knowledge and responsibilities, the task role of the leader seemed less important than his/her supportive role. Both task and supportive leader roles are addressed in the NASA Crew Office list of team competencies, as is the situational nature of leadership (Barrett, Holland, & Vessey, 2015).

Team dynamics are an important issue for crewmembers. In pre-mission surveys, ISS astronauts indicated that maintaining positive relationships with teammates would be their highest priority during the mission (Stuster, 2016). As is evident in their journal entries, astronauts "actively worked to maintain interpersonal harmony by cooperating, avoiding certain topics in conversation, and other sincere acts of comradeship" (Stuster, 2016, p. 33). Interpersonal friction or tension was rarely mentioned in the journals. This finding is consistent with research by Kanas and colleagues (2006). Their surveys of astronauts and cosmonauts did not reveal any significant decline in team cohesion over the course of a mission. Likewise, crewmembers' daily logs included few reports of negative experiences. However, Kanas et al. (2006) noted that almost half of the negative incidents referred to interpersonal (intra-crew and crew–ground) issues.

While team cohesion, collaboration, and conflict are less of a concern for the relatively short-duration missions on the ISS, they pose a significant risk for future long-duration space exploration (LDSE) missions. A mission to Mars will present challenges to crewmembers no one has experienced before. A vivid description of what lies ahead is provided by Salas et al. (2015):

> Imagine living and working in a small, confined space with five other teammates for over a year. Your team needs to complete a series of scientific experiments and perform other rigorous tasks, eventually exploring a distant location in a dangerous, even life-threatening mission. If you are successful, you will then spend 6 months "commuting" home in the same confined quarters and challenging conditions. During this assignment, headquarters cannot provide you with quick advice or coaching, because there is up to 20-minute communication delay (one-way), but you still need to coordinate as a team with people back at headquarters. From a personal perspective, during these 2 to 3 years, you cannot see Earth, feel gravity, or spend time with your family. And if you or any of your teammates are having a bad day, you cannot simply go out for a walk or call in sick. (pp. 200–201).

Mars missions will involve considerably more crew autonomy than is the case in current spaceflight operations. The move to more crew autonomy will require that some of the expertise currently held by flight controllers will have to be shared by crewmembers. This shift will result in more diverse crews as mission-relevant expertise will be distributed among their members. As crews act more self-reliantly, the parameters of their teamwork also will change. This issue became clear in semi-structured interviews Mesmer-Magnus and colleagues (Mesmer-Magnus, Carter, Asencio, & DeChurch, 2016) conducted with astronauts and members of their support teams (psychologists, trainers, operations managers, flight directors, and engineers). The discussions suggested that teamwork during LDSE missions will be considerably more fluid than in current missions. For example, an overlooked facet of crew performance during current missions is that crewmembers alternate between working independently and collaborating with others on tasks. The need to switch between individual and collective work will likely be more pronounced during LDSE as crewmembers will have more distributed expertise and unique responsibilities. Likewise, crewmembers will switch between (sub)teams, collaborating with different crewmembers as necessitated by different tasks. Fluid work structures and team memberships create complex, multilevel, and dynamic influences on team cohesion that measurements will need to address.

These insights are reflected in current efforts to advance new methodologies for assessing team cohesion and coordination during LDSE missions. The goal is to develop measures that capture team cohesion as a "dynamic, multi-faceted, and multilevel phenomenon" (Salas et al., 2015, p. 202) and that can be automated to provide crewmembers with timely feedback and guidance. The latter requirement is particularly important for LDSE to enable crews to be self-regulating. For example, a team of organizational psychologists and engineers is developing a high-precision wearable sensor system that can capture multimodal data indicative of teamwork interaction and process dynamics, such as intensity of physical movement, distance and changes in distance between team members, heart rate, and vocal characteristics (duration, interval, and intensity of vocalization; Kozlowski, Chang, & Biswas, 2013). Crewmembers wear a badge with a sensor array and a receiver/server that continuously records data and distributes them via a web interface for viewing in real time. Currently the badges are being field-tested in space analog environments. Ultimately the goal is to identify benchmark patterns characteristic of a well-functioning team to which the incoming data stream can be compared and, if an anomaly is detected, countermeasures to restore cohesiveness can be triggered (Kozlowski, Chao, Chang, & Fernandez, 2016). Another research approach (Miller, Wu, Schmer-Galunder, Rye, & Ott, 2011; Wu, Rye, Miller, Schmer-Galunder, & Ott, 2013) focuses on the automated analysis of crewmembers' written communications (log entries) using linguistic indicators of team effectiveness (Fischer, McDonnell, & Orasanu, 2007) to characterize team dynamics (e.g., who talks to whom), group identification (e.g., ingroup vs outgroup), emotional valence (positive/negative), and politeness. By tracking the social dynamic of a crew over time, sudden and unanticipated shifts can be flagged and used to initiate appropriate interventions.

Effective teamwork in space (among crewmembers) and on the ground (among mission controllers) are but two ingredients of successful space missions. As the safe return of Apollo 13 so vividly demonstrates, much of the success of human spaceflight hinges on communication and cooperation between space crews and mission control.

Collaboration between Mission Control and Space Crew

As with any collaborative work, successful collaboration between mission control and a space crew depends not only on members' technical expertise but also on skilled teamwork. Team processes and competencies that have been associated with multiteam effectiveness are communication, shared team and task models, and leadership (Kanas & Manzey, 2008; Mathieu et al., 2001).

Communication between mission control and crew is usually passed through one position in MCC, the capsule communicator, with the Flight Director and other flight controllers following the conversation over the space-to-ground voice channel. This centralized approach to mission control–crew communication has several benefits. The CAPCOM as information hub ensures that communication proceeds in an orderly fashion and thus facilitates maintenance of common ground within mission control and between mission control and crew. A second advantage of this communication process is that it affords multiple layers of checks. Flight controllers provide input not to the CAPCOM but to the Flight Director who needs to give approval before a message is transmitted to the crew, and other flight controllers partake in the decision making over a voice loop. A further advantage stems from the fact that CAPCOMs typically are members of the astronaut corps. Since they share knowledge and expertise with the crew and understand their perspective, they are uniquely suited to foster common task and team models between crew and mission control; i.e., a shared understanding of how and when teams need to coordinate with each other, and each team's capabilities, resources, expertise, and task responsibilities and constraints. They are *boundary spanners* who build connections and trust between teams (Landon, 2017). As one astronaut noted in a diary entry

> Capcoms can really make your day. But there's a big difference between being upbeat and being seriously upbeat . . . if a capcom is always saying "great job" or "awesome work" it only goes so far. The best capcoms are the ones who are to the point, give you the info you need succinctly, and sound like they know what you're doing . . . a sense of trust builds between the capcom and the crew and positive remarks from the capcom have more meaning.
> (Stuster, 2016, p. 28)

Moreover, in their capacity as astronauts, CAPCOMs represent the crew in mission control and may speak for them when events prevent mission control from consulting with the crew. One such instance is provided by Kranz (2000) in his account of the deliberations preceding the decision on the return path for Apollo 13. "In the scramble to secure the command module, we didn't have a chance to brief the crew or even get their opinion on the return path" (p. 318). Nonetheless, he felt that with the CAPCOM present they had a representation, that "Lousma, as their representative, would speak out if needed" (p. 318).

Several conventions governing ground–crew communication aim to support shared mental models and facilitate team coordination (Uhlig, Mannel, Fortunato, & Illmer, 2015). As mentioned earlier, all operational communications between CAPCOM and the crew are conducted on a specific voice channel and everybody in mission control is required to attend to the conversation. Daily planning conferences between crew and mission control take place twice a day—at the beginning and at the end of the crew's work day—to review or preview their schedule, and discuss mission-relevant events and issues on-board or on the ground. These conference calls ensure that team members have a shared understanding of upcoming tasks, task progress, and the task environment. Detailed procedures that have been worked out in advance enable crewmembers to perform many assigned tasks without having to communicate with mission control. However, some crew-to-ground communications are mandated. These include progress updates—mainly to inform mission control that a task has been completed—as well as the transfer of information that is otherwise not accessible to mission control, such as readings on devices not integrated with the ISS's data management system. Some of these communications facilitate coordinated actions between the teams. For example, the crewmembers need to let mission control know that they have reached a particular step in a procedure, and before they can continue, they need to wait for mission control to execute some action (e.g., change a system configuration) and to OK the crew's next step. Operational communications between crew and mission control are highly formalized, consisting of a call sign to identify the addressee and caller and the specification of the voice channel, followed by a succinct statement; more complex information is presented in meaningful *chunks*. Messages are promptly acknowledged, with either a generic phrase, such as "copy," or a shortened repeat of the message content. These conventions aid mutual understanding by ensuring that an addressee attends to the message (call sign), that messages do not overly tax his/her working memory (brief messages or chunking of content), that a message has been received and understood ("copy"), and that a misunderstanding is caught right away (repeat of message content).

While communication conventions support team members' evolving task and situation understanding, timeline and task procedures encapsulate the more static aspects of team members' shared knowledge. In current space operations, the multi-team system (MTS) of space crew and mission control "is driven from the ground" (Vessey, 2014, p. 141) with mission control in a leadership and monitoring role while the crew takes action as directed by or in consultation with ground. Mission planning is accomplished by mission control typically a year prior to launch and results in a detailed schedule for crew activities such as science experiments or EVAs that crewmembers are expected to adhere to during the actual mission (Kortenkamp, 2003).

Likewise, expertise on ISS systems resides with flight controllers, as does responsibility for any data management. The crew therefore needs to rely on mission control for processing system data and for catching and troubleshooting irregularities, as well as for making any changes to system settings. The Flight Director is in charge of operations in MCC, and is also the de facto leader of the MTS comprised of mission control and crew. When missions go according to plan, crew–MCC collaboration is governed by the mission timeline and standard operational procedures. MTS leadership by the Flight Director is called for when events occur that require adaptive collective responses. In these situations, the Flight Director is the person who specifies what needs to be done, by which team or teams, and when actions must be accomplished and completed.

Gene Kranz's leadership during the Apollo 13 crisis provides an excellent example of MTS leadership. He handed over the Control Room to his flight director colleague, Glynn Lunney, and assembled his team of controllers, program officers, and engineers in a separate room to *work the problem*. Together they defined the problem space. In Kranz's words: "thinking out loud so that everyone understood the options, alternatives, risks, and uncertainties of every path" (p. 321). He then assigned the most experienced controllers to lead the problem-solving efforts in their areas of expertise.

> My three leads will be Aldrich, Peters, and Aaron. Make sure everyone, and I mean everyone, knows the mandate I'm giving them. Aldrich will be the master of the integrated checklist for the reentry phase. He will build the checklist for the CSM [command/service module] from the time we start power-up until the crew is on the water. John Aaron will develop the checklist strategy and has the spacecraft resources. He will build and control the budgets for the electrical, water, life support, and any other resources to get us home. Whatever he says goes. He has absolute veto authority over any use of our consumables. Bill Peters will focus on the lunar module lifeboat. There are probably a lot of things we have not considered and he will lead the effort on how to turn a two-man, two-day spacecraft into one that will last for four days with three men. Whatever any of these three ask of you, you will do. (p. 320)

While the teams of controllers and engineers around Aldrich, Peters, and Aaron worked on their assigned tasks, Kranz served as their liaison to Lunney and the other controllers in MCC who, in turn, were the link to the Apollo 13 crew. In addition to managing the task, Kranz was also instrumental in motivating team members, in making them believe "that this crew is coming home" (p. 321).

NASA carefully prepares astronauts and flight controllers for their joint work during missions. Spaceflight resource management courses train important team competencies that are reinforced during simulated missions (Rogers, 2010). The collaboration between mission control and the space crew is further aided by communication conventions and task procedures as well as a centralized leadership structure. However, spaceflight presents formidable challenges to MCC–space crew collaboration that may lead to inadequate communication and cooperation between the two teams.

Challenges to MCC–Space Crew Collaboration

Any remote collaboration is challenging. Because team members are spatially separated, they live in different environments and their interactions lack the immediacy present in co-located teams. Spaceflight quite literally magnifies the distance between team members and the different worlds they inhabit. This impression is captured in Figure 2 which depicts the International Space Station orbiting above Earth. It is thus not surprising that potential friction between space crew and mission control has been identified as a threat to the success of space operations. As Ball and Evans (2001) report, "[c]osmonauts and astronauts alike agreed that the most challenging interpersonal problems were not among the crewmembers but, rather, were between the crewmembers in space and the mission controllers on the ground" (p. 140). Many of these problems seem to reflect differences in the task models of crew and mission control. For example, Stuster (2010; 2016) analyzed personal journals maintained by 20 astronauts on ISS missions and noted that the main sources of work-related stress and frustration that crewmembers reported were unrealistic time estimates made by mission planners, or procedures that did not sufficiently account for their perspective, as the following quotes illustrate:

> Today was a hard day. Small things are getting to me. I am tired. I think that the ground is scheduling less time for tasks than before. So, there is very little, if any fat left in the schedule for me to use to catch up on little things during the day. (2010, p. 10)

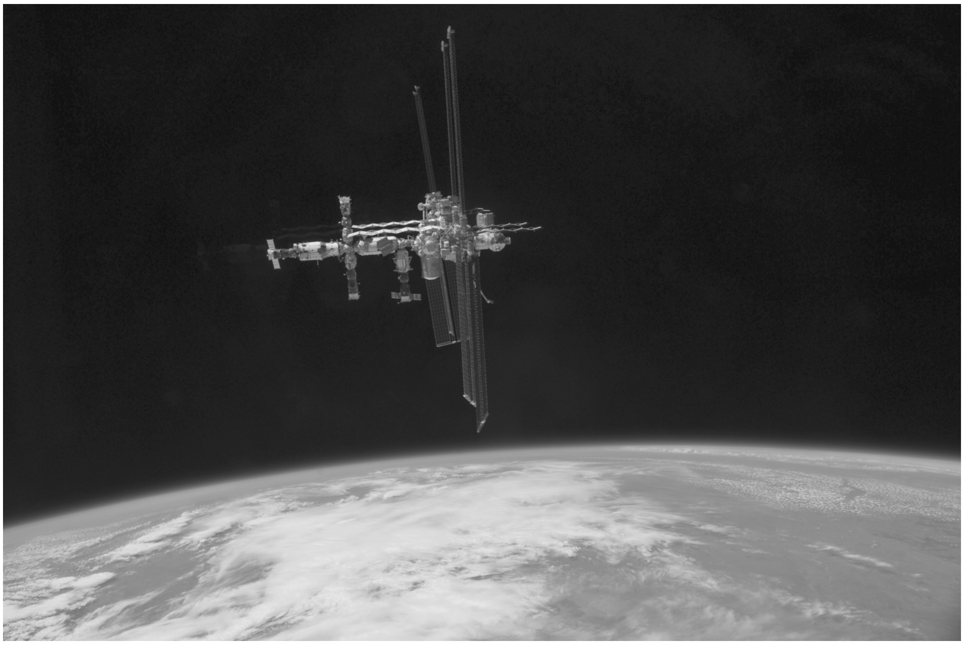

FIGURE 2 The International Space Station (ISS) as seen from the space shuttle *Atlantis*.
Image courtesy of NASA.

> The procedures are not very clear nor written in an order that makes sense for the work we are doing. They also have outdated pictures for equipment we are no longer using. In addition, they do not clearly state which steps in the procedures we will be running.
>
> (2016; p. 61)

The spatial distance between space crew and mission control may also lead to psychological closing and information filtration by crewmembers toward ground support. This phenomenon was noted by Gushin and colleagues (Gushin et al., 1997) in their analysis of crew-to-ground communications in two isolation studies lasting 90 and 135 days. They found that, over time, crewmembers talked less often with flight controllers and addressed fewer work-related themes. Crewmembers' interactions with mission control may also suffer from displacement of within-crew conflict to flight controllers. Displacement is operationalized in terms of an increase in reported negative mood accompanied by a drop in perceived outside support, and was observed during Shuttle/Mir missions as well as ISS missions (Kanas et al., 2007; Kanas et al., 2006). By portraying mission control as unsupportive or hostile, crewmembers were apparently able to deflect internal problems, at least temporally (Kanas & Manzey, 2008).

As missions travel further from Earth, delays in communication with mission control will be unavoidable. During long-duration missions and missions beyond low Earth orbit, space–ground communications will involve delays up to 20 minutes one way, a reality that poses a significant challenge to remote team communication and coordination and ultimately to mission safety and success. In an experiment conducted on the ISS, Kintz and colleagues (Kintz, Chou, Vessey, Leveton & Palinkas, 2016) introduced a communication delay of 50s while crew and flight controllers collaborated on off-nominal tasks. Team members' perceptions of their communication quality were significantly lower for asynchronous than for synchronous flight segments. The question of how best to support crew–mission control communication during asynchronous conditions was taken up by Fischer and colleagues (Fischer, Mosier, & Orasanu, 2013; Fischer & Mosier, 2014, 2015), using an integrated approach of laboratory studies and research in space analogs that included as participants current astronauts and flight controllers, astronaut-like professionals (i.e., individuals who in terms of education, personality characteristics, and age were comparable to members of the astronaut corps), and non-expert adults. Research identified communication problems associated with transmission delays (50s and 300s), underlying cognitive mechanisms, and strategies that facilitated remote collaboration under asynchronous conditions and supported team effectiveness. Analyses of the communication between remote team members revealed that transmission delays—irrespective of length—degraded the communication process and made it more difficult for team members to establish common ground. Problems included step-ons (i.e., a voice message that a remote team member had sent 50s or 300s prior was received while transmitting a radio message), disrupted message sequence (i.e., related messages by different team members, such as an answer to a question, were not adjacent but separated as other communications intervened), and outdated information (i.e., critical information was received too late). Team members exacerbated these problems by failing to adapt their communication behavior to the delayed conditions and by applying instead expectations and conventions of everyday (i.e., synchronous) discourse, causing unnecessary communications or misunderstandings. For example, team members often expected an immediate response and misinterpreted the time lag as a communication problem, or mistook a remote member's communication received immediately after their own transmission as a response to it. Well-performing teams adopted adaptive strategies, such as announcing the specific time at which to expect a transmission, or specifying the topic of a message. However, they did not consistently adhere to these strategies, especially when workload was high. These strategies were the starting point for the development of a communication protocol—a structured template to facilitate remote collaboration under time-delayed conditions. It consists of four segments (call sign, topic, message, closing) and specifies their content and organization to address the major challenges of asynchronous communication—time, conversational thread, and transmission efficiency. The protocol was implemented in several space analog studies to assess its feasibility. Astronauts and astronaut-like professionals showed high acceptance of the communicational protocol and rated it as highly effective in supporting their interactions with ground support (Fischer & Mosier, 2016).

In future exploration missions, space crews will need to manage tasks more autonomously than in current operations, although they will continue to be part of the MTS composed of members in space and in mission control. Introducing crew autonomy into the design of future space operations will impact the interdependencies that currently exist between crew and mission control teams; most notably it will involve a change in how responsibilities are going to be distributed between crew and mission control and this shift, in turn, will be associated with different information, action, and coordination requirements by the teams.

For instance in an experiment by Frank and colleagues (Frank et al., 2013), crew autonomy enabled by automated monitoring systems put the crewmembers into the role of "*doers*, responsible for performing most of the procedures associated with their assigned activities, and completing troubleshooting procedures in response to system failures and medical emergencies" while the role of flight controllers in mission control "was more supportive, advising, and guiding crewmembers as they went about their activities" (p. 3). In comparison to present-day conditions, crewmembers reported a reduction in workload during autonomous mission operations. Flight controllers, in contrast, experienced both "workload benefits and penalties" (p. 16), apparently because although workload was reduced when they were less directly involved in tasks, they spent more time monitoring systems in an attempt to understand the crew's actions. Complementary findings are reported by Kanas and colleagues (Kanas et al., 2010), who implemented crew autonomy in several space-analog studies. Mood ratings revealed that while space crews generally enjoyed working autonomously, flight controllers experienced confusion about their role when a space crew had task autonomy. These findings suggest that crew autonomy could potentially lead to a misalignment of the task and team models held by space crewmembers and flight controllers. Moreover, the long communication delays associated with space exploration may further exacerbate this problem.

Future Research

We have come a long way since the Apollo 13 incident. Astronauts live on the International Space Station for months at a time, and the teamwork between them and MCC continues to exemplify a highly successful collaboration. However, space operations will undergo radical changes as NASA implements long-duration exploration missions to Mars and other interplanetary destinations. In these missions, space crews will have to function more autonomously than in current ISS operations because communication delays due to an increased distance to Earth will eliminate the possibility of real-time assistance from MCC. Nonetheless, given the complexity of future spacecraft systems MCC–space crew collaboration will remain important to the safety and success of missions. This prediction raises a number of important research questions. Foremost we need to address what organizational changes to the current multiteam system of space crew and mission control are required to support long-duration space exploration. For example, should MCC abandon its traditional control function and act in a support capacity in long-duration space exploration? This shift, in turn, would require changes to the current (MCC-driven) leadership structure (Landon, et al., 2016). One possibility is that future space operations will involve shared leadership between MCC and the space crew; a structure in which leadership functions are distributed among the teams (Burke, Fiore, & Salas, 2003). Research is needed to determine whether and how shared leadership should be implemented; in particular, when it should be adopted and how best to allocate responsibility (e.g., tied to specific tasks, or to tactical versus strategic issues). A related question is how crew autonomy should be introduced (Vessey, 2014). Is it effective in terms of both mission safety and MTS performance to give space crews high autonomy throughout LDSE missions, or should crew autonomy be granted gradually in the course of a mission as a function of communication delay? Additionally, we need to specify the information- and knowledge-sharing requirements for effective MCC–space crew collaboration during autonomous operations, and develop team training and communication procedures that ensure common task and team models by space crew and MCC during crew autonomy.

To support this kind of research, appropriate analogs that simulate conditions of long-duration exploration missions are needed as well as participants that belong to or are representative of the target populations, that is, astronauts and flight controllers. Some natural extreme environments, such as Antarctic outposts, have been tapped as research venues similar to space operations—they are remote; inhabitants typically stay for a long period, are confined to the premises, and must wear special protective clothing to go outside of the facility; and communication with support personnel is limited. Other analog environments, such as NASA's HERA (Human Experimental Research Analog) at Johnson Space Center, and NEEMO (NASA Extreme Environment Mission Operations) in the Florida Keys, as well as HI-SEAS (Hawaii Space Exploration Analog and Simulation), an experimental analog on the slopes of the Mauna Loa volcano in Hawaii, offer more control than natural environments with respect to experimental manipulations, schedules, and tasks, but these research venues are limited in terms of the participant pool and/or duration of missions. Interestingly, the ISS has been considered as a research analog for LDSE missions; however, the real-time work occurring in the ISS limits its availability and flexibility for experimental research efforts.

A formidable difficulty for space research arises from the fact that there are logistically few opportunities per year to conduct a long-duration simulation. As a result, multiple studies with different and potentially conflicting research foci must be integrated and coordinated in the same simulation study. NASA has adopted this practice for its space analogs, so that researchers are required to adapt their work to a multi-study environment and many researchers collect data from the same simulation. Of course, multi-study simulations introduce their own problems associated with *test burnout* due to an excessive number of surveys and other measures. Researchers must recognize and respect limits to the number of measurements that crews can be expected to provide due to time limitations and workload.

Lastly, the required research inevitably involves a small sample size, limiting the possibilities for statistical data analysis. This highlights the need to collect data across simulations and to share data among researchers to boost statistical power. Again, NASA has begun to address this need by grouping simulations into *campaigns* that include several similar *missions*, and by including data-sharing agreements as part of the requirements to conduct research in the analogs. It has become clear that in order to develop a valid and viable perspective of teamwork in space operations, researchers must be as collaborative as the MTS teams they seek to understand.

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