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Crew roles and interactions in scientific space exploration

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ABSTRACT

Future piloted space exploration missions will focus more on science than engineering, a change which will challenge existing concepts for flight crew tasking and demand that participants with contrasting skills, values, and backgrounds learn to cooperate as equals. In terrestrial space flight analogs such as Desert Research And Technology Studies, engineers, pilots, and scientists can practice working together, taking advantage of the full breadth of all team members' training to produce harmonious, effective missions that maximize the time and attention the crew can devote to science. This paper presents, in a format usable as a reference by participants in the field, a successfully tested crew interaction model for such missions. The model builds upon the basic framework of a scientific field expedition by adding proven concepts from aviation and human space flight, including expeditionary behavior and cockpit resource management, cooperative crew tasking and adaptive leadership and followership, formal techniques for radio communication, and increased attention to operational considerations. The crews of future space flight analogs can use this model to demonstrate effective techniques, learn from each other, develop positive working relationships, and make their expeditions more successful, even if they have limited time to train together beforehand. This model can also inform the preparation and execution of actual future space flights.

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1. Introduction

Early in its history, human space exploration efforts focussed on goals of national prestige and engineering development. The first astronauts were military test pilots. Their professional methods, language, and values formed the culture of human space flight. Many elements of that culture persist to the present day.

Since the Apollo program, professional scientists have also served as astronauts, but their success has been measured by the extent to which they have adopted the values of operational aviation. With some notable exceptions (including Payload Specialist crew members flying on early Space Shuttle missions), they have not been called upon to exercise their scientific skills: observing, questioning, and forming and testing hypotheses. When a scientific payload flies aboard a piloted spacecraft, a scientist–astronaut often operates the apparatus, but he or she rarely designs the experiment, reduces the data, or writes the paper; furthermore, the investigation typically represents a secondary goal for the mission.

Abbreviations: AOS, Acquisition of Signal; Capcom, Spacecraft (Capsule) Communicator; CRM, Cockpit Resource Management; Desert RATS, Desert Research And Technology Studies; EVA, Extra-Vehicular Activity (spacewalking); GMT, Greenwich Mean Time; ICAO, International Civil Aviation Organization; ISS, International Space Station; LOS, Loss of Signal; MET, Mission Elapsed Time; NASA, National Aeronautics and Space Administration; NOLS, National Outdoor Leadership School; SEV, Space Exploration Vehicle; TCAS, Traffic Collision Avoidance System; TDRS, Tracking and Data Relay Satellite; UTC, Coordinated Universal Time

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It is reasonable to predict that future space exploration might follow the historical example of the development of Antarctica. If it does, then future endeavors in space will place science on a more equal footing with engineering and national renown. Future crews will include more scientists. More mission success criteria will be scientific. Pilots and engineers will still be needed for their skill in operating space vehicles, but their work will occupy less time and address fewer mission goals.

Such changes will challenge current methods of crew tasking. For the foreseeable future, as in the past, it will be unacceptably wasteful to deliver a person to space only to have them sit idle when work outside their specialty is underway. Instead, aviators and scientists will have to cooperate to maximize the mission's scientific return. When the day's duties involve flying or engineering, the scientist will assist, as scientist–astronauts have done in the past. When the day's duties are focussed on science, the pilot or engineer will participate, as the Apollo pilots did on the Moon.

Such interdisciplinary cooperation raises specific questions. How can spacecraft pilots and flight engineers help when the day's work requires scientific skills? What can scientists do to maximize the scientific contribution of their non-expert teammates? How can both overcome the differences in their technical cultures to function effectively together, especially if they have little or no time for cross-training before the expedition begins?

This paper addresses those questions. It is based on the authors' experiences in proposing, conducting, and evaluating field research; in working aboard the Space Shuttle and the International Space Station (ISS); and in serving as a spacecraft communicator in Mission Control. Preparation for the latter experiences involved thousands of hours of mission simulations in a variety of settings, including nearly a thousand hours of aircrew experience and hundreds of hours of teamwork training specifically for spacewalks in NASA Johnson Space Center's Neutral Buoyancy Laboratory. The foregoing training was informed by the lessons learned in over a hundred prior space missions conducted over a span of fifty years. Additional material for this paper comes from terrestrial space flight analogs. In many analogs, scientists and astronauts must cooperate despite having little experience in one another's specialties and limited time to train together beforehand. The authors have participated in the 2004–2005 field season of the Antarctic Search for Meteorites expedition, the 2009, 2010, and 2011 field seasons of Desert Research And Technology Studies (Desert RATS), the 2010 season of the Pavilion Lake Research Project, the 15th NASA Extreme Environment Mission Operations underwater mission, numerous field research expeditions focused on the development of volcanic terrains, two formal teamwork-oriented wilderness expeditions with the National Outdoor Leadership School (NOLS), and a winter survival exercise with the Canadian armed forces.

This paper summarizes and consolidates many of the lessons learned from the endeavors listed above. It is structured to serve as a reference manual for crews of future space analogs and flights, with consolidated lists of accepted concepts and terminology intended equally to remind experienced participants and to inform newcomers. The authors hope that this paper will help the crews of real and simulated space expeditions understand each other's perspectives, learn each other's useful techniques, and make best use of each other's professional skills. Failing that, the authors at least hope to help future crews avoid serious failures of teamwork, such as an aviator and a scientist sharing a small cockpit and not cooperating because the first thinks the second is likely to panic in an emergency, and the second thinks the first does not respect mission goals.

Besides this Section 1 and a short concluding passage in Section 6, this paper contains four sections. Expeditionary group interactions, workload sharing, standards for communication as currently used in aviation and space travel, and the "operational perspective" that is central to the success and safety of any expedition are addressed in Sections 2–5, respectively.

2. Group interactions and expedition behavior

To pilots, engineers, and scientists taught to respect only objective data, observer-dependent social interactions can appear to be an invalid topic for formal consideration. That impression is far from the truth. Formal studies of polar and space expedition crews show that group interactions are the most important driver of expedition crew members' psychological well-being [1]. Prolonged danger, discomfort, isolation, monotony, strange food, poor sleep, close quarters, limited hygiene, long work hours, and lack of privacy can strain working relationships until cooperation becomes impossible. According to cosmonaut Valery Ryumin, "all the conditions necessary for murder are met if you shut two men in a cabin measuring 18 ft by 20 ft and leave them together for two months" [2].

Group interaction problems in expeditionary environments go beyond dark humor. The third Skylab crew refused to respond to Houston for a day because they felt that Mission Control was abusing them with unreasonable work demands [1,3]. Contemporary ISS crews have reported that the ground team should allow them more autonomy [4]. On the other hand, positive group interactions can help people stay tolerant and productive under extremely difficult conditions [5,6].

Modern pilot training treats crew interactions under the heading of Cockpit Resource Management (CRM). Despite its subjective nature, aviators value CRM because it can eliminate failure of teamwork as a cause of aircraft accidents.

Related to CRM is "Expedition Behavior" [7], which is taught by organizations such as the National Outdoor Leadership School (NOLS) on physically challenging wilderness expeditions lasting weeks to months. NOLS teaches stress-tolerant interpersonal skills that produce happier participants and more efficient cooperative work.

Crew members trained in the management of working relationships can help to improve morale and reduce interpersonal problems on an expedition. Because formal teamwork training is rarely included in the academic preparation of a career scientist, this is an area where a pilot or flight engineer can contribute to a scientific mission.

2.1. Basics of expeditionary group behavior

NASA astronauts receive extensive training in group interactions as they prepare for space flight [8]. The training includes CRM exercises in the high-performance T-38 jet aircraft, expeditionary behavior courses with NOLS, and formal evaluation of group interactions with Mission Control during mission simulations and among crewmembers during Extra-Vehicular Activity (EVA, spacewalking) training.

Following NASA practice, we divide group interaction skills into the categories of self care and management, teamwork and group living, and leadership. Expeditionary self management is the ability take good care of one's own body and mind in order to stay healthy, enjoy the mission, and help (rather than hinder) the team. Teamwork and group living skills foster positive interactions between crewmembers. Leadership skills address authority, decision-making, and influencing others. Table 1 summarizes the elements of all three categories. Some of the recommendations may appear simplistic: entire books have been written on topics we express in a few words, e.g., "manage conflict well." The table is presented as a reminder for graduates of expedition behavior training, and as a primer for people without training who may nevertheless be able to improve their group interactions simply by keeping in mind the points listed there.

2.2. Special considerations for scientific exploration

Table 1 gives a set of interpersonal skills that can help on any expedition. They can also be applied to the special case of scientific exploration missions. The 2010 Desert RATS expedition (see Kosmo et al. [9]), which paired astronauts with geologists on a simulated space mission, provided opportunities to test principles of CRM and expedition behavior, especially those related to development and coaching. Crews found that pilots and engineers who learned as much as possible about the mission's scientific goals, methods, and terminology were able to make better observations, take better samples, and serve as more knowledgeable sounding boards to help their scientist counterparts formulate and test hypotheses. Similarly, scientists who learned vehicle systems and their operation to the best of their ability were able to help more during mission phases that were focused on engineering. Despite severe constraints on training time before and during the mission, crews who actively supported one another's cross-training found the operational and scientific benefits well worth the extra effort.

3. Crew tasking and workload sharing

The expeditionary behavior outlined in Section 2 is designed to build interpersonal relationships that support the safe, effective completion of work, which in turn helps make a successful expedition.

Much scientific work is done by researchers working alone or on small unstructured teams, in situations where time is plentiful, personal risk is low, and the cost of errors is manageable. These working conditions maximize creativity and scientific progress, but they may not hold on an expedition constrained by time pressure, significant risk, and low error tolerance. A pilot or engineer can contribute to scientific field work that they may not fully understand by modeling techniques for workload sharing that were developed for aviation but are also suitable for an expedition. The following paragraphs summarize some of those techniques.

To ensure right actions and trap errors promptly and without wasting the limited resource of the crew's attention, aviators use five techniques: prebriefs, checklists, backup behavior, debriefs, and active followership.

A prebrief is a short meeting in which the team leader and crew discuss the plan for an upcoming mission. It sets expectations for the day's work, seeks agreement on goals and methods, and confirms that all participants understand the operation and their roles in it. A checklist is a short, itemized, written list of steps designed to prevent any part of a larger task from being forgotten. Checklists, when designed intelligently and applied appropriately, demonstrably reduce human error. They have been successfully used in aviation for decades and are being adopted in other risk-averse fields, such as medicine. Backup behavior means that when one crewmember does a task, another confirms each step. U.S. spacecraft crews use checklists and backup behavior together to reduce potentially costly errors. One crewmember physically manipulates controls while a partner reads the checklist aloud, one step at a time, politely calling out any errors that might occur, and marking each step complete when he or she sees that the action has been done correctly. Whether or not to use backup behavior is a complex consideration, balancing the cost of an untrapped error against the loss of efficiency caused by assigning two people to a task that one could do. A debrief is another short meeting that follows a major operation or a day of work. In a debrief, crew members assess how well the operation went, both to recognize successes and to identify areas for future improvement. The latter subject is important because it motivates people to learn and improve, and helps keep newly learned lessons from being lost. It may also offend sensitive egos. Leaders can reduce the likelihood of offense by avoiding blame and by presenting lessons learned as positive things.

Active followership is helpful in many contexts. We illustrate it here with an example from a space flight analog activity that successfully tested many of the concepts for group interactions and workload sharing presented in this paper.

In the 2010 Desert RATS expedition, crews drove two planetary rover prototypes (called Space Exploration Vehicles or SEVs) on seven-day geology traverses across a volcanic field in Arizona. The authors, a professional field geologist and an astronaut without formal geology training, served as one of the crews, living together in the vehicle for the duration of the traverse. Each day they drove to two or three study sites, conducting timed

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Table 1
Elements of expeditionary group behavior.

Self care and management	
Self-care	Take good care of yourself. Ensure that your basic requirements for food, water, warmth, rest, etc. are being met. Adjust physically, emotionally, and behaviorally to difficult living circumstances.
Stability	Maintain self-control, self-confidence, and emotional stability during the expedition. Keep perspective. Accept what you cannot control, control what you can. Learn to tolerate adversity and uncertainty.
Performance under stress	Effectively perform tasks under difficult conditions. Learn to endure and even enjoy hard work and challenges. Under stress, stay positive, focused, and connected with others.
Motivation	Demonstrate motivation, productivity, perseverance, and optimism as appropriate.
Graceful handling of failures	Accept that errors happen. If you make a mistake, acknowledge it quickly, make a recovery plan, and then press on. When someone points out a mistake you are about to make, say "good catch" or "thank you."
Learning	Cultivate good judgment. Actively improve your own knowledge, technical skills, and organizational techniques. Learn from experience and take steps to improve yourself. Seek and accept critiques of your own work and interactions. Admit imperfections and personal faults, especially in interpersonal relations, and work hard to correct them.
Self-awareness	Be aware of your condition, abilities, limitations, and learning needs. Understand and effectively manage your own strengths and weaknesses for the sake of safety and performance. If you are concerned about your safety or well-being, tell someone.
Well-being	When appropriate, find a healthy balance of work, play, rest, and reflection.
Conscientiousness	Display basic competence. Organize and take effective care of your personal and work areas, materials, and assignments.
Ownership	Whether your expedition is a good experience or a bad one depends largely on how you choose to conduct yourself and interact with your teammates. The skills needed for good group interactions are fully trainable and under your control.
Teamwork and group living	
Group living and interaction	Demonstrate selflessness, empathy, open-heartedness, and respect for others. Use appropriate humor. Avoid ineffective behavior such as alienation, hostility, and blocking team progress. Prevent division among mission personnel. Do not form exclusive relationships. Never be selfish. Be as concerned for the welfare of others as you are for your own. Consider the team, not just yourself; do what is best for the group rather than what is best for you. Value honesty, diplomacy, selflessness, courtesy, competence, and good judgment. Develop an awareness of what your crewmates think is important, and demonstrate respect for it. Share common equipment and common areas equitably.
Generosity	Be generous. Bring small gifts for your teammates at the beginning of the expedition, or share a treat (candy, funny stories, etc.) partway through the mission, when everyone is starting to get uncomfortable and tired. Make and share good food.
Courtesy	Follow the example of NOLS instructors, who set the tone for their expeditions by being quintessentially polite. Say "please" and "thank you" almost every time you speak. It may sound awkward at first, but it works: late in the expedition when you and your teammates are stressed, the habit of courtesy is so well ingrained that you will continue to be nice to each other.
Kindness	Be kind to your teammates. Compliment them when they do well. Find nice things to say about them.
Initiative	Actively contribute to improve the team's morale, performance, goals, culture, and self-awareness. Assess what needs to be done, and do it. Volunteer for tough duties. Do your share, and more if you are able. Complete your own work and help others with theirs (but do not do everything for them).
Integrity	Be honest and accountable. If you can do something, say "yes" and deliver. If you cannot, clearly say "no". Take full responsibility for your own actions and words.
Followership	Seek clarity. Provide feedback to, and receive input from, your leader and teammates. Place team goals before personal goals. Watch what the leader is doing and try to make his or her job easier. (NASA astronaut culture values crewmembers whose conduct reduces, rather than increases, the commander's workload.)
Communication	Communicate well. Show diplomacy. Effectively manage conflict. Speak and be silent when appropriate. Be an active listener: paraphrase back for clarity, get clarification if needed. Give feedback to crewmates in a positive way. Speak out if you have observations or concerns that the rest of the team may not be aware of.
Coordination and monitoring	Stay aware of the team's progress and condition. Cooperate and coordinate with others. Share information and workload. Keep an eye on teammates' activities and back up their work to trap errors without confrontation or blame. Help ensure that everyone's basic requirements for food, water, warmth, rest, etc. are being met.
Cultural awareness	Be aware of the impact of national, organizational, and team culture on individual behavior. Effectively live and work with people from different cultures.
Leadership	
Situational leadership	Adapt your leadership and decision-making styles as appropriate for the situation. Work at being yourself as leader.
Modeling and coaching	Be a good role model. Set a positive tone for the mission by demonstrating the behaviors you want others to develop. Motivate and encourage growth in others. Help others see the big picture and the long view. Show that you value competence, communication, self-awareness, sound judgment and decision-making, tolerance for adversity and uncertainty, and good expedition behavior.
Goal-setting	Define and clarify your vision and goals for the expedition. Explain everyone's roles and responsibilities. Carefully balance mission goals and team development goals. Use group goals and values to guide your actions. Take risks at a level appropriate for you and the group.
Flexibility	Question norms, challenge assumptions, and welcome change. Turn challenges into opportunities. Seek creative ways to move forward. Shift your role from leadership to active followership when appropriate. Help the team to stay aware of changing conditions and adapt its performance accordingly. Remember that a leader fixated on a goal can take the team into danger if conditions change.
Decision-making	Be decisive. See choices as many options, not either–or. Give the group choices that have acceptable consequences and be clear about limits and boundaries.
Facilitation skills	Foster a climate of excellent expedition behavior and culture among teammates and with outsiders. Create an open atmosphere. Avoid an "us versus them" mentality, both among expedition members and between the expedition and remote participants such as control centers, if applicable. Strive to enhance harmony and performance. Manage conflict well. Help create what you want to see.

Table 1 (*continued*)

Leadership communication	Communicate clearly in briefings, one-on-one conversations, and team meetings. Listen well. Demonstrate diplomacy. Seek feedback from others. Be as open to receiving feedback as you are to giving it. The feedback you provide to others should be timely and specific, and should be oriented toward their growth and improvement. When discussing a problem, begin by acknowledging your own role in it, no matter how small. As leader, choose a leadership style, and tell the group what it is. Tell the group what you expect from them, and what they can expect from you. Conduct prebriefs to clarify expectations for upcoming work and debriefs to recognize technical and teamwork-related results from completed work. Debriefs should highlight areas where the team worked well together and areas of focus for future improvement.
Inclusion of remote participants	If your expedition has an operations base or mission control center, keep it fully appraised of the field team's health, status, and progress.
Resource management	Resources include fuel and equipment, time, team morale, and the skills and abilities of team members. There may be times when your teammate is not just your best resource, but your *only* resource. Effectively use all of your team's available skills, experience, resources, and information to solve problems and achieve positive results. Direct, organize, facilitate, and support effective use of team resources by yourself and others.
Mission monitoring	Effectively monitor the team's changing situation and environment. Stay aware of working conditions and obstacles to performance. Keep the group informed as the situation changes. Change the plan as needed and act accordingly.

"EVAs" outside the vehicle to obtain imagery and geologic samples. For the EVAs, crews wore street clothes but carried cameras, instrumented backpacks, and geological sampling tools. The two crews in the field worked with each other and with a remote "Mission Control" which included an Apollo-style science team whose task was to use the data collected by the field crews to understand the geology of the area.

Following aviation standards, each morning began with a prebrief of the day's plan. The prebrief included Mission Control, the science team, and the field crews.

During driving traverses, the astronaut served as crew leader while piloting the vehicle and operating its systems. The geologist worked as an active follower by running checklists, cross-checking the driver's work to trap errors, and monitoring the clock and the day's schedule to predict how the day's running surplus or deficit of time would affect upcoming operations. When not helping the driver, the geologist added scientific value by recording out-the-window observations and by conducting technical discussions with the geologist in the other SEV and the remote science team. Desert RATS crews experimented with crew tasking by occasionally swapping the driving and support roles. Doing so provided welcome diversity in assignments for the crew. Unfortunately it also reduced the scientific value of the traverse because driving occupied the geologist's attention and the astronaut was less well trained to make geological observations. The crews therefore chose to keep the astronaut and the geologist in their primary roles during most driving traverses.

When the vehicle stopped at a study site, crew roles changed. The astronaut parked the vehicle, followed checklists to configure its systems for uninhabited operation, and readied equipment for an EVA. Meanwhile the geologist took context photographs using the SEV's external cameras, recorded out-the-window observations of the work site, and identified specific areas for physical sampling. Splitting the crew this way made efficient use of time during a period of high workload, but did not allow them to back up each other's work. Crews found by experience that working separately was an acceptable tradeoff in this specific case, because time was short and the impact of untrapped errors was small. (The trade would likely have been unacceptable in a real space expedition, where a mistake in EVA preparation could have life-threatening consequences.) Just before exiting the vehicle, the crew conducted a short prebrief to confirm the duration and scope of the EVA.

Desert RATS EVAs were devoted to geologic sampling and observation. For a complete description of Desert RATS scientific tasks and methods, see Hurtado et al. [10]. The authors divided their efforts to make best use of the strictly limited time outside the vehicle. On EVAs, scientific value was added when the geologist leading the activity was collecting samples and recording observations. Other tasks wasted the geologist's time and expertise. The astronaut therefore served as an active follower by doing as much as possible of the unskilled labor, which included taking context and panorama photographs and fetching, carrying, and stowing samples and tools. When the geologist did not need help, or when the topography of the study site made it better for the two crew members to work separately, the astronaut collected samples and recorded observations (including sample size, weight, color, texture, and density) that added some scientific value even without specialized knowledge or terminology. At the end of the EVA, the astronaut arranged the samples on the SEV's aft deck so that the geologist could record systematic descriptions of them, which in turn freed the astronaut to stow and secure the sampling tools for the next driving traverse. Informal polling of the Desert RATS team after the field test suggested that this division of labor made very efficient use of limited EVA time.

Inside the vehicle after an EVA, the geologist took final context photographs and recorded his or her impressions of the geology while the astronaut secured the suit ports and prepared the vehicle for travel. Both crew members then conducted a short debrief to summarize the geological and operational knowledge gained, and commenced driving to the next study site. Finally, at the end of the work day, the field crews debriefed the completed operation with Mission Control and the science team.

Although future space exploration missions will have different goals and crew compositions, the Desert RATS experience suggests that similar active followership with flexible leadership and tasking will maximize the time and attention the crew can devote to science.

Besides offloading unskilled tasks from scientists, pilots and flight engineers can add scientific value even if they have not had the kind of extensive classroom and field training that was provided to the Apollo crews. The essence of scientific observation is a clear description of what the observer sees. It need not include formal terminology. In particular, an aviator able to estimate sizes, distances, and durations can use that ability to characterize stationary objects on the ground as well as moving objects in the air. A clear description of a volcanic rock forming an elongate mound two meters high with a crack down the middle should lead the remote science team to conclude that the astronaut is observing a tumulus (e.g. [11]), from which they can infer a significant geologic process even if the astronaut does not use that technical term.

A scientist can help an untrained crewmate produce valuable science beyond basic observations. In the case of a geological expedition like Desert RATS, the geologist can set a positive tone early in the expedition by establishing a consistent vocabulary of commonly used terms and concepts. This will help the astronaut understand the geologist's descriptions and discussions. The geologist can also make effective use of driving time between work-sites, explaining terminology to his or her crewmate while documenting the traverse. Similarly, if the geologist uses a word the astronaut does not understand, the astronaut should say so, and the geologist should define it in terms that make sense to a non-expert. It is worth taking a few seconds of mission time to explain a concept that might help the astronaut make a valuable observation later.

Although the EVA crew may have a direct communication link to a wealth of scientific expertise on the remote science team, the crew geologist has primary responsibility for reminding his or her EVA partner about the science goals to be addressed while "boots are on the ground" outside the vehicle. In Desert RATS, this was done as part of the EVA prebrief. Geologists also used prebrief time to confirm that their astronaut partners knew any new scientific terminology that the geologist and the science team might use at that work site. In addition to prebriefs inside the vehicle, Desert RATS crews made use of time spent waiting for depressurization and mandatory leak checks in the airlock or suit port [12]. These operations took several minutes during which crews could review the EVA's plan, goals, and terminology. These discussions were more effective when the vehicle was parked in an orientation that allowed the geologist to point out features of interest. Note that on a real space mission, the time frame of EVA preparation is likely to be too busy for such reviews; site-specific training and reminders will have to occur earlier.

In scientific discussions and debriefs, Desert RATS crews noticed a natural tendency for scientists to dominate the discussion and for astronauts to tune out. For the sake of crew unity and skill development, all crew members should fight this habit. In Desert RATS, geologists worked actively to involve astronauts in scientific discussions to the greatest extent possible. They frequently asked astronauts whether their thoughts were consistent with those of the scientific experts. Geologist crewmembers also conducted impromptu science discussions between the two rovers during their evening free time (see Bleacher et al. [13]), providing even better opportunities for this kind of involvement. These discussions were free from the stress of the day's operations, allowing plenty of time for all crew members to ask about the day's scientific observations and the development and testing of hypotheses across the whole traverse. Scientists on future mixed crews can help their non-expert crewmates cooperate and improve by actively including them in such discussions.

Extensive Apollo-style cross-training for both scientists and aviators on future space exploration missions will enable crew members from both backgrounds to cooperate smoothly as outlined above. Analog tests, however, rarely provide such thorough preparation. For a successful mission under such circumstances, all participants should strive to learn their crewmates' strengths and weaknesses, divide labor in a way that uses those strengths to best advantage, and help one another improve in areas where their skills are less well developed.

4. Communication

Modern expeditions rely on radio communication to share information among participants. When the radio link is good and time is plentiful, unstructured discussions among scientists add considerable value to a science mission, and informal conversations among crew members and between the crew and their families, friends, and colleagues at home improve morale. But when the radio link is noisy, delayed, or time-limited, or when operational or safety-related information must be communicated, formal radio techniques become more valuable. Pilots and flight engineers who have talked to air traffic control, spacecraft crew members who have communicated with Mission Control, and spacecraft communicators (Capcoms) who have worked in Mission Control can contribute their skill in radio communication to improve operational information flow. Just as expeditionary scientists should teach their operational counterparts relevant scientific concepts and terminology (see Section 3), experienced radio operators should consider it part of their job to help crew members less familiar with radio technique to improve their communication skills.

Aviation radio protocol [14,15] was developed to provide the best possible understanding with the fewest possible syllables, in an environment where a misinterpreted call on a noisy, crowded radio channel can have deadly consequences. The overriding goal of aviation radio communication is to foster understanding. A misunderstood radio call is often worse than no call at all. Second only to understanding is brevity: transmitting the needed information quickly, so as not to waste shared resources of time and bandwidth. The language of aviation is not perfect and it sounds strange to untrained ears, but it has been tested for decades in billions of airplane operations around the world and, with minor adjustments [16,17], in all NASA piloted space missions and space flight analog expeditions. Its long and widespread use argues that it will be kept for upcoming space missions. It may also serve as the basis for the development of standards for operational communication based on text or other media which may augment or replace voice in the more distant future.

Aviation radio techniques include a structured format for common radio calls; specific times, events, and places where radio reports are required and expected; use of the International Civil Aviation Organization (ICAO) Phonetic Alphabet for spelling out words and numbers; use of the 24-h Coordinated Universal Time clock; standard terminology; monitoring of signal quality; and permitted use of plain language when standard phrases do not convey meaning well enough. Below we present a summary of each technique, as a reminder for experienced aviators and as a primer for beginners. We also provide consolidated glossaries of common terms to serve as a field reference in future space flight analog tests.

4.1. Format for common calls

People are more likely to understand a transmission if it gives expected information in an expected order. A standard radio call begins with the name of the party being called, then who is calling. If applicable, the caller should say "where" he or she is: position, altitude, or the radio frequency being used if there is more than one possibility. Then the caller should say why they are transmitting, if it can be put briefly. For example:

"Albuquerque Center, NASA 901, 390." (Albuquerque Air Route Traffic Control Center, this is the aircraft with the call sign NASA 901, flying at an altitude of 39,000 ft.)

"Station, Houston, we have updates for your robotics procedure, advise ready to copy." (International Space Station, this is Houston Mission Control. We need you to make some changes to the written instructions you will use to operate the robotic arm. Tell us when you are ready to write them down and we will read them to you.)

4.2. Standard reports

In aviation and human space exploration, controlling authorities define times, situations, and places where radio reports are required so that all listeners can maintain awareness of one another's status and location. Typically these occur at the beginning or ending of a clearly defined, important phase of the operation. In aviation, a radio call is required when a pilot changes to a new air traffic control frequency or executes a missed approach. Shuttle crews made a call when they began the final approach to dock with the ISS. NASA EVA crews call to verify mechanical interface operations, electrical and fluid connector mates and demates, and any changes to the attachment hooks of their safety tethers. Future space missions and analog tests are likely to have their own rules for mandatory radio reports.

4.3. The ICAO Phonetic Alphabet

Aircraft and spacecraft cockpits are noisy, and radio channels can be cluttered with static and multiple simultaneous conversations. Under such conditions, it can be difficult to distinguish between B and P, D and T, and other similar-sounding letters. The ICAO Phonetic Alphabet (Table 2) assigns an unambiguous name to each letter. Expedition members should use the phonetic alphabet whenever they must speak a single letter or spell out a word or acronym over the radio. Future international expeditions may have to modify or augment the ICAO standard if they use characters in other alphabets, such as Cyrillic.

The phonetic alphabet includes words for each numeral. Some are deliberately distorted to make them more distinct from each other. (But note that in the United States, many pilots and controllers deviate from the standard and pronounce "three," "four," and "five" colloquially.) Since many numbers can be indistinguishable on the radio (e.g., "fifty" and "fifteen"), numbers should be spelled out one digit at a time using the names given in the table. The decimal point can be called either "point" or "decimal." In aviation, calls specifying altitudes

Table 2
ICAO Phonetic Alphabet.

Character	Name	Pronunciation
A	ALFA	"al-fah"
B	BRAVO	"brah-voh"
C	CHARLIE	"char-lee"
D	DELTA	"dell-tah"
E	ECHO	"eck-oh"
F	FOXTROT	"foks-trot"
G	GOLF	"golf"
H	HOTEL	"hoh-tel"
I	INDIA	"in-dee-ah"
J	JULIETT	"jew-lee-ett"
K	KILO	"key-low"
L	LIMA	"lee-mah"
M	MIKE	"mike"
N	NOVEMBER	"no-vem-ber"
O	OSCAR	"oss-cah"
P	PAPA	"pah-pah"
Q	QUEBEC	"keh-beck"
R	ROMEO	"row-me-oh"
S	SIERRA	"see-air-rah"
T	TANGO	"tang-go"
U	UNIFORM	"you-nee-form"
V	VICTOR	"vik-tah"
W	WHISKEY	"wiss-key"
X	XRAY	"ecks-ray"
Y	YANKEE	"yang-key"
Z	ZULU	"zoo-loo"
1	ONE	"wun"
2	TWO	"too"
3	THREE	"tree"
4	FOUR	"fow-er"
5	FIVE	"fife"
6	SIX	"six"
7	SEVEN	"sev-en"
8	EIGHT	"ait"
9	NINE	"nin-er"
0	ZERO	"zee-ro"

in hundreds of feet have special rules for use of the words "hundred" and "thousand." For example:

15 Is pronounced "wun fife."

6400 Is pronounced "six fow-er zee-ro zee-ro" or, if an altitude in aviation, "six thousand fow-er hundred."

29,300 Is pronounced "too nin-er tree zee-ro zee-ro" or, if an altitude in aviation, "too nin-er thousand tree hundred."

1.072 Is pronounced "wun point zee-ro sev-en too" or "wun decimal zee-ro sev-en too."

Certain common abbreviations which are hard to confuse with other words (either because of unique pronunciation or because the meaning is clear from context) are commonly spoken without using the phonetic alphabet. In aviation, the Traffic Collision Avoidance System (TCAS) is commonly called "tee-cass" on the radio. In NASA space-to-ground communication, Mission Elapsed Time (MET) is pronounced using the conversational names of the letters, "em-ee-tee." These are exceptions to the rule. If an operator does not know how to pronounce an abbreviation or acronym, he or she should use the phonetic alphabet as a default. Understanding is paramount, and it is better to sound too formal than to transmit a confusing message.

4.4. Coordinated Universal Time

Aviators use Coordinated Universal Time (UTC), a 24-h military-style clock based on Greenwich Mean Time (GMT). Times given on the radio should be read as four digits, the first and second indicating the hour after midnight and the third and fourth the minute after the hour. All time calls are assumed to be UTC unless otherwise stated. Leading with "time" or "UTC," or following with "Zulu," is allowed to reduce the chance for confusion: "yoo-tee-see wun tree fow-er wun" for 1:41 PM GMT; "time zee-ro ait tree fife zoo-loo" for 8:35 AM GMT. Times on local clocks can be stated by appending the word "local" or the name of the time zone (e.g., "time wun fow-er wun fife local", "time zee-ro six fife zee-ro Central"). If there is no chance for confusion, a time may be given as only two digits to indicate minutes past the current hour.

Shuttle flights used Mission Elapsed Time, a 24-h clock time that counted days, hours, minutes, and seconds since launch. The ISS uses UTC because it is already a standard in use by the program's many partner nations. It is likely that future deep-space exploration missions will be international in nature and will also use UTC.

4.5. Standard ICAO and NASA terminology

Good use of standard phraseology reduces the chance of communication errors. In the aviation community it is seen as a mark of a professional pilot. Table 3 is a glossary of selected aviation radio terms and their meanings. It is adapted from the Federal Aviation Administration's *Pilot/Controller Glossary* [15] with a few additional terms used by NASA for human space flight [16,17]. Standard terminology can help participants with different native languages understand each other. The aviation lexicon is used worldwide and is therefore familiar to many aviators whose knowledge of English is otherwise limited.

4.6. Monitoring signal quality

Many of the words in the glossary relate to transmission and reception quality. This is no accident. Signal quality is central to effective communication, and good radio operators remain alert to it at all times. If they receive a call that is hard to understand, they ask the caller to clarify or repeat it.

A long period of silence is often a clue that something is wrong with a transmitter or receiver. So is the lack of an answer after calling once, waiting a judicious interval, and calling again. If things are too quiet, radio operators should make sure they have not inadvertently turned their volume down, double-check that they are on the right frequency, and confirm that their microphone is not stuck in the transmit position (the "stuck mike" in Table 3) which can jam all communication traffic on the frequency.

If an operator suspects that transmissions are not being heard correctly, he or she should ask "how do you hear me?" Common responses include "loud and clear," "faint but readable," "broken," "faint, broken," and "unreadable." Some operators use five-point scales for loudness and clarity. "Five by five" means "loud and clear." Numbers below five indicate weaker volume and worse clarity, with one indicating barely audible or nearly unreadable.

To test a voice circuit for quality, volume, and consistency, a common technique is to give a "five count:" saying "Testing one, two, three, four, five…five, four, three, two one" in a normal tone of voice. The duration of the count gives the other operator enough time to adjust their volume control and other settings.

4.7. Plain language

The phraseology in Table 3 may be confusing to people encountering it for the first time. Even experts find that it is sometimes not adequate. Because correct understanding overrides all other considerations, including adherence to the standard, radio operators who feel like their meaning is not understood should use whatever words they need to get their message across.

If the standard glossary proves cumbersome or inadequate for communicating concepts that are discussed repeatedly in an independent operation (such as a spaceflight analog), it is permissible to invent new, simple, unambiguous terms to be used in radio traffic for that operation. New nomenclature should be created with clarity and brevity as the highest priorities, and everyone involved in the operation should agree on it before it is put into use.

4.8. Rhetoric

Standard structures and terminology are the building blocks of effective radio communication, but assembling those pieces into good calls takes additional skill.

Table 3
Glossary of selected aviation and NASA radio terms.

ADVISE INTENTIONS—“Tell me what you plan to do.”
ADVISE READY TO COPY—“I want to give you information to write down. Tell me when you have pencil and paper ready, and I’ll read it to you.”
AFFIRMATIVE—“Yes.”
BLOCKED—“The last radio transmission was distorted or interrupted by another simultaneous transmission.”
BREAK BREAK—“I am interrupting your ongoing conversation with an urgent announcement.” Use only in case of danger.
BROKEN—“Parts of your last radio transmission were not received.”
CHECKING—A NASA term used to answer an astronaut’s call to Mission Control. Essentially means “STAND BY,” but with the added meaning that “the Flight Control Team needs a few seconds to formulate the answer to your question.”
COPY—“I understand.” Formally, this means “I wrote it down so if you ask me to repeat it verbatim later, I will be able to.”
CORRECTION—“The last thing I said was incorrect. Correct words follow.”
DISREGARD—“Cancel my transmission in progress” or “ignore my last transmission.”
EXPEDITE—“Be quick about it, or you will be in danger.” Contrast with IMMEDIATELY.
FAINT—“The volume of your transmission is too low for easy understanding.”
GO AHEAD—“Proceed with your message.” Not to be used for any other purpose; specifically does not mean “move forward.”
GOOD WORDS—NASA term. Means the same as READBACK CORRECT.
HOT MIKE—Means the same as STUCK MIKE.
HOW COPY?—Means the same as HOW DO YOU HEAR ME?
HOW DO YOU HEAR ME?—“Tell me the volume and clarity with which you hear my transmission.”
I SAY AGAIN—“I will repeat my last message.”
IMMEDIATELY—“Do it now. You are in danger.” Contrast with EXPEDITE.
IN WORK—NASA term. “I am starting to do, or already doing, what you asked.”
I WILL CALL YOU BACK—NASA term. “It is going to take more than a few seconds to respond to your question or request. I will call again when I have a response ready.”
LOUD AND CLEAR—“Your transmission quality is very good.”
MAYDAY—The international distress call. Repeated three times, it means “I am in grave danger and request assistance.”
NEGATIVE—“No,” or “permission not granted,” or “that is not correct.”
NORDO—“No radio.” Indicates that an aircraft cannot communicate with other aircraft or with air traffic control.
NO JOY—“I tried to do what you asked, but I was not successful.”
ON MY MARK— NASA term. “For precise time coordination between us, I am going to give you a short countdown to a specific event and say ‘mark’ at the instant when it happens.” Example: “Houston, Atlantis, pulling the Air Data 3 circuit breaker ON MY MARK. Three, two, one, mark.” The pace of the countdown should be one number per second.
OVER—“My transmission is ended. I expect a response.”
READABLE—“Your transmission quality is imperfect but I can still understand you.”
READ BACK—“Repeat my transmission back to me.”
READBACK CORRECT—“As requested, you correctly repeated my previous transmission back to me.”
READY TO COPY—“I have pencil and paper and am ready to write down information.”
REQUEST (information or permission)—“Please tell me (information),” or “please grant me (permission).”
ROGER—“I received all of your last transmission” or “I hear and understand.” Not a valid answer to a yes-or-no question.
SAY AGAIN—“Repeat your last transmission.”
SAY (position, altitude, heading, airspeed, etc.)—“Tell me your current (position, altitude, heading, airspeed, etc.)”
SPEAK SLOWER—“Speak more slowly so that I can understand you.”
STAND BY—“I heard your last transmission but cannot answer right now. Please wait for a few seconds while I attend to higher priority duties. I will get right back to you.” “Stand by” does not mean AFFIRMATIVE or NEGATIVE. When you tell someone to “stand by,” he or she will wait for you to call back. If the delay becomes longer than 10–15 s you should call back. If you already know that the delay will be longer, say “roger, I will call you back” instead of “stand by.”
STUCK MIKE—“Someone on the channel is continuously keying their microphone, interfering with other calls and transmitting potentially embarrassing ambient sounds.”
THAT IS CORRECT—“The understanding you have is right.”
TRANSMITTING IN THE BLIND—“I am not sure that anyone can hear this transmission, but am sending it anyway in case someone can.”
UNABLE—“I am not able to comply with your instruction, request, or clearance.”
UNREADABLE—“The last radio transmission was garbled or distorted and could not be understood.”
VERIFY—“Please confirm my understanding.”
WHEN ABLE—“You don’t have to do it right now if you’re busy with higher-priority tasks, but do it at the next opportunity.”
WILCO—“I have received your message, understand it, and will comply with it.” Saying “roger” before “wilco” is redundant.
WITHOUT DELAY—Means the same as EXPEDITE.
WORDS TWICE—(a) As a request: “Communication is difficult. Please say every phrase twice.” (b) As information: “Since communications are difficult, every phrase in the following message will be spoken twice.”

Good radio calls are phrased so that the receiving party does not have to ask for clarification. They include all relevant information without cluttering the channel or wasting the listener’s time.

A good radio call states the most critical information first, in case the call is cut off prematurely. For calls that demand a quick response, especially in case of danger, the caller should give the needed action first, then confirm that it was done correctly, and finally explain why the action was needed. If time permits, and if it is reasonable to expect that the radio link will remain good, an operator can say what the problem is first, then give the requested action, and finally confirm that the other party did it correctly.

Good radio calls use a professional yet friendly tone of voice. Even the slightest trace of frustration, impatience, or sarcasm in an operator’s voice can ruin a previously healthy working relationship. Instead, operators should focus on a tone of voice that builds a positive rapport. The sound of the caller’s voice should make the receiving party want to help the caller. "Please," "thank you," and "I apologize" are not in the standard glossary, but they are not out of place in professional radio traffic.

A good radio call contains no jargon, slang, chatter, profanity, nicknames, or figures of speech. It uses standard terminology correctly. It is comprehensible to people who are learning English as a non-native language: an important consideration for space exploration missions which employ crewmembers from other nations.

4.9. Radio technique

Beyond the considerations discussed above, a number of other techniques contribute to competent use of the radio.

Skilled radio operators acknowledge all calls within a few seconds, saying "roger" if they hear and understand, or "stand by" if not yet able to give a response to a complex call. In aviation, pilots often indicate that they heard and understood a radio transmission by simply saying their call sign as a response. If a radio listener hears a call but does not respond at all, the caller does not know whether the listener got the message. The caller then has to decide whether to risk irritating the listener by repeating the call. Worse, the caller may suspect the listener has a radio failure, and must decide whether to use a backup transmitter or ask another radio operator to relay a message. Either way it causes needless concern and effort. Much trouble can be spared if operators answer every call promptly.

In accordance with the leadership principles discussed in Section 2, the focus of communications should be allowed to change, as appropriate, to maximize efficiency and information flow for the task at hand. Good radio operators hold low-priority calls that would interrupt a more critical conversation. At the same time, they know when their own message is urgent enough to justify saying "break break" and intruding into another call.

Experienced radio operators anticipate upcoming frequency changes and gaps in the radio link, and make agreements for re-establishing contact when the link is restored. In Low Earth Orbit, the time when a spacecraft is predicted to come into radio contact with a relay station is called Acquisition of Signal (AOS). Loss of Signal (LOS) occurs when the spacecraft leaves that asset's line of sight and the communication link is broken. On Shuttle flights, a solid communication link was present most of the time through the constellation of Tracking and Data Relay Satellites, TDRS, pronounced "tee-driss". A planned loss of contact that lasted more than a few minutes was unusual. Mission Control kept track of expected gaps in coverage and warned the crew ahead of time, then called again when the link was restored. Such calls can become tiresome if there are too many of them. For normal operations on ISS, which also use TDRS, routine LOS and AOS calls have been dropped by mutual agreement between the crew and Mission Control. ISS does receive a courtesy call from Mission Control when an approaching communications gap threatens to cut off an ongoing conversation.

Good radio operators listen before transmitting. In aviation, it is often possible to get needed information by paying attention to conversations between air traffic controllers and other aircraft on the frequency. Also, keying the microphone indiscriminately will likely interrupt other ongoing conversations. Two stations simultaneously transmitting on the same frequency generally jam each other, so that neither can get their message across. As in polite conversation, it is best to wait for an opening before talking.

If there is no response to a call, an experienced operator waits 10–15 s before trying again. It is possible that the person on the other end heard the first call, but is doing a higher priority task and cannot answer instantly.

Two simple techniques can improve the fluidity of radio calls. The first is to subvocalize a call before keying the microphone to transmit it. The second is to write down the message before transmitting it. The latter technique is especially helpful for long calls, but it takes time to prepare.

Some radio systems cut off the first syllable of a transmission if it is spoken too soon. This problem by can be avoided by keying the microphone and then pausing for a half-second before speaking. A common Capcom technique is to add a throwaway syllable ("and") at the beginning of each transmission: "And Station, Houston, Space-to-Ground 2 for stowage…"

If transmission volume is weak at normal voice level, the problem may lie with the position of the microphone. Some microphones are very sensitive to distance from the speaker's mouth. Good radio operators place the mike almost touching their lips, near the corner of the mouth. A microphone placed straight in front of the mouth transmits a burst of wind noise every time the speaker makes a "P" sound. Only as a last resort should an operator try to compensate for low volume by speaking louder. Doing so can cause fatigue, which can in turn make the caller's voice sound strained or irritated.

4.10. Non-critical conversations

Aviation radio techniques are intended for brief, formal interactions that are critical to flight safety, restricted in scope, and occur over a period of minutes or hours. For multi-day missions, operators must often exchange higher volumes of less immediate, less critical information. Aviation radio techniques do not cover this case. When risk is low and time allows, people should be free to conduct normal conversations using natural language. Doing so will provide complete understanding while fostering healthy cooperation among team members. The last is especially important to prevent division between crews in space and flight controllers on Earth.

In NASA's human space flight operations, it is common to prearrange times of the day, not during complex or hazardous operations, when the crew and Mission Control can summarize how the day's work is going, give detailed reports, and transmit lower-priority information. On ISS, such conferences are scheduled at the beginning and end of each work day. Conference times are reserved so that

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they do not conflict with other tasks, which would put pressure on the crew to cut them short.

4.11. Multiple communication channels.

Air traffic control uses one radio channel at a time. Everyone on that frequency must listen to it and share opportunities to speak. Space exploration, which can involve multiple interacting vehicles and crews, may require more radio traffic than a single voice channel can support. ISS commonly uses two channels at once. When Shuttles were docked to ISS, the combined vehicles used at least three simultaneous voice channels to talk to one another and to their respective flight control teams.

Divided radio channels are harder to keep track of. Someone must listen to all of them and make sure that contradictory information is not being transmitted on independent channels. When more than one radio channel is available, all participants should know by prior agreement which ones to use under which circumstances. One possibility is to distribute communication to different channels according to task type. ISS often reserves one channel for operation of the vehicle's systems, and another for scientific research.

EVAs are hazardous operations where two cooperating crew members keep their microphones open all the time and Mission Control must attend to every word they say. Experience on Shuttle and ISS has shown that an EVA cannot effectively share a channel with unrelated operations.

The 2010 Desert RATS expedition successfully tested a multi-channel communications concept in which two vehicles traveling together shared a radio channel with each other and Mission Control. When they stopped to conduct two simultaneous EVAs, one crew remained on the common channel. The second crew switched to a different channel for their own EVA to keep the conversations from interfering. Each EVA crew shared its radio channel with an independent science team, while Mission Control monitored both channels. Before changing radio channels, crews made a formal announcement on the common channel. That call included the planned duration of the EVA and the time when the second crew expected to return to the common channel. After the EVA, the crew returned to the common channel with another formal call. This technique reduced uncertainty about who was listening where, and would have provided Mission Control with potentially critical safety information if the second crew had failed to check in on time.

4.12. When the radio link is not enough

Radio equipment can fail, and radio operators can make mistakes that compromise the link. Skilled operators know what to do if communication is unexpectedly lost. Typically this means having a "Comm Lost" plan ("NORDO Procedures" in aviation). A Comm Lost plan is a formally established set of actions for the team to take if they unexpectedly lose the ability to talk to each other. A good Comm Lost plan specifies which backup communication resources will be tried at what time and in what order, what vehicle flight paths and system configurations should be used to minimize risk, and how long participants should wait before taking action. Expedition participants should make Comm Lost plans before the mission begins. Doing so raises awareness about the possibility that communication assets might fail and encourages participants to develop techniques that might allow work to continue without a radio link.

A specific element of a Comm Lost plan is hand signals. Hand signals are useful if radio contact is lost while line of sight remains. They can also allow communication among nearby teammates while keeping the radio channel clear for higher-priority transmissions, such as a scientific field note during a Desert RATS EVA. If voice communication is lost but video remains, it is possible to communicate with hand signals in the field of view of a camera. NASA's EVA astronauts are taught to use hand signals as a backup to the radio link [18].

Crews should establish hand signals for simple messages such as "I'm OK, are you?" "I can't transmit," "stop," and "go that way." Standard and familiar scuba-diving and formation-flying hand signals are good choices. As with spoken communication, understanding is key and ambiguity must be avoided. In particular, the "thumbs-up" can mean "OK" or "ascend" and "thumbs-down" can mean "not OK" or "descend" depending on whether aviation or scuba-diving standards are in use. Either standard is acceptable, but everybody involved in the operation must agree on which to use. Table 4 is a list of NASA, aviation, and diving hand signals that may be useful for science expeditions.

4.13. Delayed communications

Future exploration of deep space will involve communications with significant speed-of-light delays. Robotic space exploration projects have developed techniques for exchanging information promptly and accurately despite significant delays. Current work in NASA space flight analogs includes investigating new methods (such as augmenting voice calls with text messages) for human participants to compensate for speed-of-light delay. The results will be presented in a future paper.

5. The operational perspective

Scientific research is often carried out in conditions where danger is low, resources are plentiful, errors and delays may be acceptable, and there is plenty of time to make reasoned decisions. Space is a much more demanding environment. Safely accomplishing useful work in space requires a mindset called "operational thinking." Pilots, flight engineers, and experienced field scientists are trained to think operationally and can contribute their perspective to make a science mission safer and more effective. Crew members with limited operational experience may need to adopt these methods to succeed in the mission environment. Elements of operational thinking include prioritizing action over explanation, minding the clock, managing resources attentively, anticipating and minimizing errors, maintaining checklist discipline,

Table 4
Selected hand signals from NASA, aviation, and diving.

Message	Hand signal
1	Extend index finger vertically.
2	Extend index and middle fingers, separated from each other for visibility, vertically.
3	Extend index, middle, and ring fingers, separated from each other for visibility, vertically.
4	Extend all four fingers, separated from each other for visibility, vertically.
5	Extend all four fingers and thumb, separated from each other for visibility, vertically.
6	Extend index finger horizontally.
7	Extend index and middle fingers, separated from each other for visibility, horizontally
8	Extend index, middle, and ring fingers, separated from each other for visibility, horizontally.
9	Extend all four fingers, separated from each other for visibility, horizontally.
0	Curl fingers around, touch tip of thumb to tip of index finger to enclose a circle.
Decimal point	Poke index finger toward partner.
I can't transmit	Hold hand flat, thumb and fingers together, and pass back and forth in front of your mouth.
I can't receive	Hold hand flat, thumb and fingers together, and pass back and forth by one ear.
I feel so-so	Point index finger at self, then hold hand horizontally with thumb and fingers spread and tilt it back and forth a few times.
Are you OK?	Point at partner, then touch index finger tip and thumb tip to enclose a circle, remaining fingers spread.
I'm OK	Point at self, touch index finger tip and thumb tip to enclose a circle, remaining fingers spread.
Go that way	Hold hand flat, thumb and fingers together, and gesture twice in the desired direction. Point index finger at self first to indicate "I'm going that way." Point at another person first to indicate "Please go that way."
Stop	Raise a clenched fist.
I need help	Wave one or both outstretched arms above your head.
Yes	Big exaggerated head nod.
No	Big exaggerated head shake.

making quick and correct decisions, and staying aware of the situation.

Focusing on action rather than explanation is a key difference between the values taught to pilots and those taught to scientists. In a dangerous and time-constrained environment, it is more important to react swiftly and correctly to problems than to cogitate upon their causes. In aviation, the airplane keeps moving forward, and the crew cannot stop to solve theoretical problems. If an engine quits, an operational thinker will take the correct actions to keep the crew and vehicle safe before trying to figure out why the engine quit.

An ongoing operation is a slave to the clock. Time is always limited. But environments change and equipment fails, making delays inevitable. Operational thinking means knowing the day's timeline and tasks, anticipating possible sticking points, and making and sharing plans to avoid, minimize, and recover from delays. It means watching the clock, constantly monitoring the mission's progress against the plan, knowing when and how to adjust that plan, and striving to get back on schedule when delays occur. Operational thinkers complete work as early as possible in case of later setbacks. If unable to finish one task, they switch to another so they can continue to make progress.

Time is not the only limited resource that constrains an operation. Attentive management of other resources such as fuel, food, and water is a key part of operational thinking. Experienced operators frequently check their supplies of critical resources, comparing predicted versus actual quantities to detect any possible loss or over-consumption. They manage those supplies proactively, for example by calculating "bingo" times, which mark the point at which an aircraft must turn around and return to base or else run out of fuel. Tools, consumable equipment items, and spare parts—anything without which the mission cannot proceed as planned—must be protected from loss and managed to prevent shortages.

In a time-constrained and dangerous environment, human errors can create unacceptable delays and risks. Unfortunately, no operation involving human beings will ever be free from such errors. Operational thinking includes anticipating likely errors and discussing them in prebriefs so that participants are ready to prevent or minimize them. It also includes backing up the work of others (when time and resources allow) to make sure that it is completed correctly.

As discussed in Section 3 above, checklists are a proven way to reduce errors that cause harm and delay. Operational thinking means following checklists whenever appropriate. Good checklist discipline includes verifying that all steps are completed in order with no omissions, informing other crew members when beginning a checklist, reducing distractions that might divert attention away from a checklist in progress, and announcing "checklist complete" when all the steps have been done. A person with an established habit of checklist discipline may get a nagging feeling if he or she forgets to finish a checklist. In aviation or spaceflight, that feeling might save the mission or the lives of the crew.

Good operational thinkers are decisive. They can balance conflicting priorities, make sound decisions despite time pressure and insufficient data, revise their judgments according to new data, and accept the consequences of their decisions. Operational decision-making requires continuous assessment of incoming mission

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information to identify which issues most deserve the crew's limited attention.

The last and most important element of the operational perspective is situational awareness. As with aspects of group interactions (Section 2), entire books have been written about situational awareness. Only a brief summary is possible here. The term means mindfulness, in the face of constant change and inevitable distractions, of the physical environment, the progress of the mission, and the condition of the crew. Situational awareness is easily lost. Airplanes have run out of fuel or flown into the ground while their crews troubleshot trivial subsystems issues, and mountaineering expeditions have ended in disaster when delays grew in worsening weather [19]. Good operational thinkers maintain situational awareness and use all available resources of information and experience to cross-check their understanding. They constantly question whether their perceptions are both complete and correct. They include the physical and mental condition of themselves and their crewmates as a key part of the situation. They recognize that fatigue, hypothermia, and hypoxia can stealthily impair judgment, performance, and situational awareness itself.

6. Conclusion

The future scientific exploration of space will be more successful if it finds a harmonious balance between the observing and questioning skills of its scientists and the operational skills of its pilots and engineers. With some notable exceptions, seeking such a balance has not often been a primary goal of previous human activity in space. Terrestrial space-flight analog projects provide valuable opportunities for astronauts and non-astronauts, working under environmental and operational conditions more forgiving than those of space flight, to learn how to integrate the capabilities of experts with very different backgrounds. In this paper, we have argued that exploration missions structured like scientific field expeditions, with additional emphasis on expeditionary behavior, workload sharing, structured communication, and operational thinking, are likely to make the best use of the participants' professional skills.

Crew training for real space missions provides aviators and scientists with considerable experience and cross-training in one another's areas of expertise, plus ample time to form healthy working relationships. This paper may be helpful to them early in training. It may be more valuable to participants in spaceflight analog activities who have less experience outside their own professional communities and less time to work out, from first principles, how spacecraft pilots and flight engineers can contribute to a science expedition, how scientists can foster scientific skills in their non-expert teammates, and how both can cooperate despite the differences in their backgrounds. Long experience in real and simulated space flights has shown that attending to those considerations helps pave the way to success on missions of scientific exploration.

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