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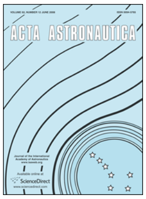

Crew autonomy for deep space exploration: Lessons from the Antarctic Search for Meteorites

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ABSTRACT

Future piloted missions to explore asteroids, Mars, and other targets beyond the Moon will experience strict limitations on communication between vehicles in space and control centers on Earth. These limitations will require crews to operate with greater autonomy than any past space mission has demonstrated. The Antarctic Search for Meteorites (ANSMET) project, which regularly sends small teams of researchers to remote parts of the southern continent, resembles a space mission in many ways but does not rely upon a control center. It provides a useful crew autonomy model for planners of future deep space exploration missions. In contrast to current space missions, ANSMET gives the crew the authority to adjust competing work priorities, task assignments, and daily schedules; allows the crew to be the primary monitor of mission progress; demands greater crew accountability for operational errors; requires the crew to make the most of limited communication bandwidth; adopts systems designed for simple operation and failure recovery; and grants the crew a leading role in the selection and stowage of their equipment.

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1. Introduction

> “Ultimately, the goal should be to have near complete crew autonomy in preparation for missions beyond LEO.” Astronaut Ronald J. Garan, ISS Expedition 27–28 flight engineer.

Past and present space missions owe their success to cooperation between crews in space and controllers on Earth, who help manage flight systems that are too numerous and complex for crews to operate alone. In turn, that cooperation relies on frequent, fast, high-volume exchanges of voice calls, spacecraft commands, telemetry, and other data. The beneficial partnership between crew and ground will be less effective in future deep-space exploration missions, in which communication will suffer from distance-related bandwidth limitations and significant speed-of-light delays. Both will impair the ability of the control center to provide timely monitoring and assistance to the crew. The crew will therefore have to assume more tasking and more responsibility themselves. They will have to be more autonomous.

Space flight crew autonomy has been the subject of a handful of studies and experiments (e.g., [1–5]). It is a subset of the more mature field of flight segment autonomy, which includes automation of onboard systems to take on more of

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Abbreviations: ANSMET, Antarctic Search for Meteorites; CDR, spacecraft crew commander; D/L, downlink; FD, Flight Director, the leader of the flight control team in the Mission Control Center; ISS, International Space Station; KB, kilobyte; LEO, low Earth orbit; Mars DRA 5.0, NASA Human Exploration of Mars Design Reference Architecture 5.0; NASA, National Aeronautics and Space Administration; NSF, National Science Foundation; PI, Principal Investigator; STS, Space Transportation System (Space Shuttle); U/L, uplink; USAP, United States Antarctic Program.

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the functions of a ground control center. Automation will be one of the grand challenges of deep space exploration. In this report, we focus exclusively on factors directly relating to the human beings on the mission: command, transportation, communication, system control, logistics, and work planning.

Past human space exploration missions have never ventured beyond the Moon, and experience with crew autonomy has been limited to communication outages and rare in-flight emergencies. The human space exploration community thus has a limited intrinsic knowledge base upon which to build new operational concepts for autonomous crews.

Other kinds of exploration, however, can offer valuable insights about certain aspects of crew autonomy. Expeditions in deep caves, high mountains, and underwater often operate with little outside support. (NASA, ESA, and other space agencies have used such terrestrial environments for tests conducted as "analogs" for space missions, e.g. [6].) Another example is the Antarctic Search for Meteorites (ANSMET), a long-running planetary science research project that has sent more than 45 "crews" of researchers to remote field sites on the southern polar icecap for 6-week expeditions. Working in Antarctica is similar in many ways to working in space (e.g., [7]). Several astronauts have participated in ANSMET in recent years. One has said, "If you've done ANSMET, you've done long-duration space flight" (D. Pettit, pers. comm.). A crucial difference between ANSMET and space flight is that ANSMET crews operate without relying on a control center. They are largely autonomous.

This paper identifies and discusses aspects of crew autonomy where ANSMET can provide instructive guidance for planners of future deep space exploration missions. It is based on the authors' experience in both human space flight and Antarctic exploration. One of us (S.G.L.) participated in the 2004–2005 and 2012–2013 seasons of ANSMET, served as an International Space Station (ISS) Capcom in Mission Control for 8 years, and flew as a crewmember aboard Space Shuttle mission STS-122, an ISS assembly flight. The other (R.P.H) is a veteran of 22 field seasons in Antarctica and has been the field team leader and Principal Investigator of the ANSMET project since 1991.

This report is divided into six sections. Following this section (Section 1), we describe aspects of crew autonomy on ISS missions today (Section 2), on a thoroughly developed future Mars mission concept (Section 3), and on ANSMET (Section 4). In Section 5 we identify and discuss specific areas where ANSMET provides a flight crew autonomy model for future exploration missions, and make recommendations for the hardware, software, and operational concepts that crews will use on those missions. The paper ends with a short conclusion (Section 6).

2. Crew autonomy on the International Space Station

The ISS represents the current state of the art in human space flight. This section summarizes the features and attributes of ISS operations that relate to crew autonomy.

2.1. Command

The Flight Director (FD) in Mission Control is nominally the commanding authority of the ISS. But in practice, command of the ISS resides jointly with the FD and the crew commander (CDR) onboard. The CDR has primary decision authority for issues related to crew safety. The ground team prioritizes onboard tasks and resolves schedule conflicts in accordance with formally established ground rules and constraints. Both the ground team and the CDR monitor the progress of daily operations.

For science investigations, crew members generally act only as equipment operators. They are not involved in experiment design or planning, or in the interpretation or presentation of the results. ISS crews do not prioritize competing science activities or make decisions that could affect the outcome of onboard experiments. Those decisions are made on the ground, usually by investigators outside the control center who have little or no direct communication with the crew.

ISS crews are not the primary "stewards" of spacecraft hardware. That is, they do not have the deepest knowledge of its design and operation and they do not make decisions that could affect its health. When following established procedures or instructions from the control center (almost always the case), they may not even bear primary accountability for human errors in its operation. ISS crews commonly seek permission from the ground before operating data, power, thermal, and other systems central to the vehicle's function. This is especially true if the operation is unplanned. Even given that permission, crews typically stop work and request assistance from the ground if anything unexpected happens while they are commanding core systems. For decisions that could potentially damage the vehicle, the crew defer to the ground team, whose deeper specialized knowledge and around-the-clock awareness make them the better decision-making authority—and also the responsible, accountable party—for ISS systems.

ISS crews are selected by managers in their respective space agencies. ISS CDRs have little or no role in the crew selection process. Cohesion among the crew members is developed as they progress together through the 2.5-year flight training syllabus.

2.2. Transportation

Transportation to and from ISS via Soyuz spacecraft is planned years in advance. A dangerously ill ISS crewmember could potentially be returned to Earth (necessarily along with his or her two Soyuz crewmates) within hours or days. On-demand rescue missions to the Station are not considered feasible.

2.3. Communication

ISS crews have near-constant voice communication with a responsive ground control center about 90% of the time, on at least two independent radio channels. Dozens of e-mail messages pass up and down every day. Every week the crew receives new, complex "procedures," sets of work instructions for onboard tasks that include explanatory diagrams, photographs, and sometimes short embedded video clips. In turn, the crew may downlink to the ground hundreds of high-resolution digital photographs every day. Text, imagery, and other electronic files are exchanged with the ground via the Ku-band communication system, which is scheduled about 60% of the time during routine operations. When available, the Ku-band system can also carry four simultaneous channels of downlink video. The ground team often uses video to observe the crew during complex or critical operations, allowing them to verify the crew's work and potentially trap errors. The Ku-band system also supports an Internet-protocol voice channel for the crew's private use.

Communication between the ground and ISS includes private medical conferences. These are scheduled regularly for routine matters, but can also be arranged with a few minutes' notice if there is an urgent need for a crewmember to consult privately with the flight surgeon.

2.4. *System control*

Although ISS crews commonly operate ancillary equipment on the vehicle, they rarely interact with the vehicle's core systems. Those systems are largely operated from the ground via near-constant telemetry and about 3000 commands per day. The vehicle is so complicated that the crew could not learn all there is to know about it during a reasonable flight training curriculum. Instead, most system knowledge resides on the ground. Except for emergencies requiring immediate action to save the crew and simple problems correctable by onboard automation, the ground is prime for the response to most failures, especially those that can be addressed with electronic commands. For failures requiring a hands-on response, ISS crews do have access to general repair procedures. But often when a non-time-critical malfunction happens, ground personnel rewrite the procedure to clarify it and to make it specific to the precise failure that occurred. They re-verify the new procedure with mockups and simulators on the ground, and then send it up for the crew to execute. This process takes several days.

2.5. *Logistics*

Cargo bound for the ISS is manifested months to years in advance. Except for a strictly limited allowance for personal items, the crew has little say in what does or does not fly. Ground personnel prepare almost all items for flight and load the spacecraft.

Crews unpack equipment arriving on ISS and stow it according to instructions from the ground. Because many items on ISS are stowed by one crew and retrieved by other crews months or years later, human memory does not suffice for inventory management. Instead there is a complicated system of barcodes, optical scanners, and stowage location codes that interfaces with a database maintained in the control center. Unfortunately, any error in stowing items onboard, in reporting stowage locations to the ground, or in updating the database results in searches for lost items that can be frustrating for crew and ground alike.

Resupply missions to ISS occur at intervals of weeks to months. Ground personnel track the use of consumables and equipment onboard and prioritize items for future resupply flights. Most cargo is loaded weeks before launch. Resupply missions are subject to schedule slips and cannot flex to meet changing crew needs. A sudden critical need for an item onboard can sometimes be accommodated by late changes to the manifest of the next resupply flight. More commonly, such needs cannot be met until months later. Because of the long response time, and because any launch to ISS has a chance of failure, the ISS maintains “skip cycle” reserves of consumables such as oxygen and water sufficient to last for months. The ISS also carries a massive inventory of spare parts intended to last for the foreseeable lifetime of the vehicle.

2.6. *Work planning*

Ground personnel plan the work day for ISS crews, who follow an electronic schedule that is updated by themselves and by the ground many times a day. Tasks sometimes take longer than planned. A job that exceeds its allotted time period conflicts with the next item on the schedule, forcing a decision about whether to leave the first incomplete and start the second, or to complete the first at the expense of the second. Such decisions are usually made by the ground. If the schedule needs major modification, ground personnel replan and update it.

3. Crew autonomy on a Mars mission

The following discussion is based on NASA's Human Exploration of Mars Design Reference Architecture 5.0 [8], henceforth called Mars DRA 5.0. Although many other Mars mission concepts exist, they are all subject to the same limitations of physics and technology and are likely to differ only in the details. The general picture, especially with regard to crew autonomy, will be similar.

The basic structure of a Mars mission will resemble that of past and present space flights. There will be a flight crew led by a commander. A control center on Earth will monitor and assist remotely and act as “headquarters” for the mission. There will be two major differences with respect to present operations. First, the Mars ship's great distance from Earth will limit communication. Even at the speed of light, it can take many minutes to send a radio call and receive an answer. This delay makes communication difficult [9] and restricts the amount and timeliness of assistance the ground can provide, forcing the crew to be more autonomous. Distance also limits the bandwidth of the communication link. Second, the distance between the planets and the geometry of their orbits effectively prevents crew, cargo, and rescue flights except at specific launch opportunities occurring at 26-month intervals. Crews on Mars will likely use assets emplaced by robotic spacecraft on earlier launch opportunities in addition to the equipment and supplies they bring along with them.

3.1. *Command*

As in present-day ISS operations, leadership of a Mars mission is likely to be shared between the crew commander onboard the spacecraft and the flight director in Mission Control. The CDR will have primary responsibility for crew safety. But communication delay and bandwidth restrictions will reduce the ability of the ground to help in many situations, especially those that develop quickly. The CDR must therefore be responsible for a greater number of possible failure scenarios than ISS CDRs are today. Similarly, the ground will be prime for prioritization of preplanned tasks, but the CDR will have to make changes to tasking in cases where there is not enough time to consult with the ground. The CDR and the control center will likewise both monitor the mission, but the control center's information will necessarily be late and sparse.

For science tasks on a Mars mission, the broad planetary science community on the ground will likely set high-level priorities, but any science-related decisions that are not worth waiting tens of minutes for will have to be made on the spot. At least one crewmember, representing the scientific community, must have the expertise and authority to make those decisions.

As with ISS operations today, ownership of the flight vehicle and other Mars mission hardware will probably reside with the ground, not the crew. But restricted communication will force a Mars crew to assume a greater personal role in equipment stewardship than do ISS crews. Along with this increased authority for action will come increased accountability for operational errors.

The crew of a Mars mission will likely be selected by managers from the space agencies involved in the mission, with little input from the CDR. As with ISS today, crew cohesion will be developed during the long pre-flight training flow.

3.2. Transportation

As noted above, flights to and from Mars are constrained by astrodynamics. Unplanned early crew return and responsive rescue flights are not possible in Mars DRA 5.0.

3.3. Communication

Deep space exploration will take explorers hundreds of millions of km from Earth. Such great distances impose delays on radio transmissions. The worst case for Mars is a 44-min delay between asking a question and receiving an answer. For a period of weeks around superior conjunction (when Earth and Mars are on opposite sides of the Sun), radio communication may not be possible at all. Distance also reduces the amount of information that can be sent, even with powerful transmitters, sensitive receivers, and large antennas. The number of receivers worldwide that can field transmissions from deep space is limited, and they must be shared with other spacecraft exploring the solar system (e.g., [10]). The result is that the control center will have less information from a Mars spacecraft than it does today from ISS. That information will always arrive late, and there will be periods when no downlink from the Mars ship is available. Information generated onboard the spacecraft during those intervals must be stored and transmitted later, or else discarded.

Voice communication with a delay of more than a few seconds is very difficult. Normal back-and-forth conversations are impossible, and voice communication begins to resemble an exchange of messages on telephone answering machines. The challenges of delayed voice communication are discussed in detail elsewhere [9]. They combine to make delayed voice communication inefficient, unsatisfying, and prone to errors.

The same timing and bandwidth limitations will apply to exchanges of text messages and electronic files, at the same time that the problems of delayed voice force more mission communication traffic to proceed via text and files. Exchange of still photos, and especially of high-bandwidth video, will be similarly hobbled, reducing the ability of the ground control center to stay aware of events on the spacecraft and to provide imagery to the crew that supports their technical work and morale.

With delays and bandwidth limitations, private medical conferences between surgeons in the control center and crews in deep space will be ineffective in an emergency, and may be unsatisfying even for routine reports. A Mars mission is therefore likely to include a physician on the crew.

3.4. System control

Speed-of-light delays and restricted bandwidth affect spacecraft telemetry and commands at least as drastically as they affect communication between people. Operating relatively simple robotic spacecraft with communication delays of minutes to hours is a mature science (e.g., [11]), but piloted ships are an order of magnitude more complicated, and human lives are at stake. On a Mars mission, humans and machines onboard the spacecraft will have to operate systems that must be monitored in real time, or that could potentially come to harm before a telemetry signal could reach Earth and mitigating commands travel back to the ship. This will be a far cry from the current operational mode of ISS (see Section 2.4). The ground may operate onboard systems that change only slowly, or that are capable of safing and recovering themselves in case of an error or malfunction. Because it is possible to employ many more experts in a control center than on a spacecraft, the ground will still be the prime repository for system knowledge, but the need for onboard action in case of a rapidly-developing situation will force the flight crew to know more about the core vehicle systems than ISS crews do today. A Mars crew will also have to assume a greater role in failure response, again with emphasis on malfunctions that need quick corrective action.

3.5. Logistics

As with unplanned rescue or evacuation flights, responsive resupply missions are not possible in Mars DRA 5.0. Because of this limitation, and because of the long mission duration, crews of future Mars flights are likely to play a greater role in the manifesting of materiel for their expeditions. Clothing, personal items, and especially food will represent a significant fraction of the mission cargo, and crews will want to select those items individually. Ground personnel will likely pack the spacecraft as they do today, but once in space the crew will want to organize the storage of items themselves, both for their own convenience and to reinforce their spatial memory for finding things later. A remotely-managed stowage system is likely to waste precious crew time and cause unneeded irritation, especially given the potential for long delays between asking where a needed item is kept and receiving the answer.

Spare parts and reserves of consumable commodities for a Mars mission will be limited by spacecraft mass and volume constraints.

3.6. *Work planning*

As on ISS today, most daily tasking on a Mars mission will be planned by the ground. But the communication barriers imposed by distance will make it more difficult for the crew to consult with the ground when they want to change the ordering of their tasks. When a job runs long and must either be terminated or continued at the expense of another activity, the crew must have the knowledge and authority to replan the day themselves. This is a non-trivial issue. Many activities onboard a spacecraft affect core systems interdependently, or are constrained by conditions that change with time such as lighting, spacecraft attitude, and communication coverage. Flight control teams for the ISS, and formerly for the Space Shuttle, include an operator whose full-time task is to plan and re-plan crew activities in real time. That operator's work will have to be assumed by the crew of a Mars mission, in addition to their other tasks.

4. Crew autonomy in the Antarctic Search for Meteorites

The Antarctic Search for Meteorites is less well-known than the ISS and deserves some description here. ANSMET expeditions have traveled to Antarctica every year but one since 1976 and have collected over 20,000 meteorite specimens, including rare and scientifically important ones from the Moon and Mars. The meteorites are initially characterized and curated at NASA Johnson Space Center in Houston, Texas, with long-term curation at the Smithsonian Institution in Washington, DC. Although meteorites fall no more commonly on Antarctica than anywhere else, Antarctica is the best place to find them. The cold dry climate preserves meteorites, the scarcity of Earth rocks makes meteorites easier to spot, and the flow and erosion of the ice concentrates meteorites in certain locations marked by solid “blue ice” at the surface. Funds for ANSMET field work have been provided by the National Science Foundation and by NASA. When funding and logistics allow, ANSMET may deploy as two field teams: a mobile reconnaissance group of four people that explores areas identified from remote sensing as potentially containing meteorites; and a six-to-eight-person systematic search team that goes to a place known to be rich in meteorites and recovers as many as possible using a methodological approach.

A typical ANSMET mission profile begins with the team members meeting in late November in Christchurch, New Zealand, the primary logistics support point for the United States Antarctic Program (USAP). They convene at the Clothing Distribution Center for training and Extreme Cold Weather clothing issue. The next day they make their 4000-km “Ice Flight” to McMurdo Station, Antarctica, on a military cargo plane. For the next 10 days they stay in McMurdo to gather more field gear; select and pack food for field camp; complete “snow school” (an overnight field training trip on the ice near McMurdo); learn and practice crevasse rescue techniques; and crate, palletize, and document 10,000–25,000 kg of materiel for air transport.

ANSMET teams deploy via ski-equipped aircraft to their search sites, typically 1500–2500 m above sea level on the south polar plateau. The sun is above the horizon 24 h a day. Air temperatures are near $-20\,^{\circ}\mathrm{C}$, and wind chill factors frequently reach $-40\,^{\circ}\mathrm{C}$. When the team arrives at the work area, they set up a field camp of two-person Scott tents. They may use snowmobiles and sledges to traverse to neighboring search areas not directly accessible by aircraft. Field seasons usually last 6 weeks. Team members use snowmobiles to systematically sweep for meteorites on blue ice, and go on foot to search in glacial moraines. Poor weather, such as high wind, snowfall, drifting snow, or thick overcast and flat light that make travel dangerous, commonly prevents searching on a quarter or more of the days the team spends in the field.

ANSMET field camps are autonomous except for expensive satellite telephone communication and aircraft resupply flights. Via satellite phone, team members can talk with friends and family in their home countries. When necessary, team leaders can confer with specialists in McMurdo, including Mac Ops (for daily news and status updates), Fixed Wing (to keep abreast of changes to the aircraft schedule), the Mechanical Equipment Center (for information about field equipment), and Medical (for issues related to crew health). All of those institutions exist to support ANSMET and other Antarctic science projects; they do not direct field teams the way ground control centers direct space flight crews. Resupply flights might occur only twice during the season. They deliver mail and critical spares, and remove trash and unwanted equipment. Medical evacuation of an ANSMET team member by aircraft has occurred a handful of times in the project's history.

An Antarctic field camp is a difficult environment, but not as difficult as deep space. Supplies of air and water are unlimited. Rescue and resupply are possible, so illnesses and system failures are less likely to be fatal. Antarctic field equipment is not constrained by extreme mass limitations. An expedition member with “cabin fever” can leave the tent and go for a walk. But like a Station expedition or a flight to Mars, an ANSMET expedition is a months-long journey far from home with a dangerous outside environment. ANSMET crew members live in cramped quarters with a small group of international co-workers, isolated from family, friends, and the rest of the world. They endure long work days and difficulties with basic life functions such as eating and sleeping.

Because of its similarity to a space mission and its high degree of crew autonomy, ANSMET provides potentially useful insights for planners of future human deep-space exploration missions. The following sections summarize aspects of ANSMET relevant to crew autonomy.

4.1. *Command*

The Principal Investigator (PI) of the ANSMET project usually leads the field team. The team includes an experienced mountaineer whose primary duty is to keep the participants safe from crevasse falls, cold-related injuries, and other hazards. The PI prioritizes all work in the field. The PI and the mountaineer together monitor the progress of daily operations.

The mission of ANSMET is to gather meteorites for scientific study. Most of the team members are planetary scientists who are very familiar with the characteristics of the samples they are collecting. Some participants may later study meteorites they found themselves. (Note, however, that ANSMET team members have no special privileges regarding the specimens they recover. They, and all other scientists, obtain Antarctic meteorite samples for study by making formal requests to panels of impartial NASA and Smithsonian curators.) The PI is personally responsible for the success of the field season and makes all decisions that trade competing science goals against one another (such as where to search next), or that trade science against other priorities (such as whether or not to search in marginal weather conditions).

ANSMET teams borrow most of their equipment from the NSF depot at McMurdo Station. The PI and the mountaineer are the stewards of the borrowed equipment, responsible for field maintenance and accountable for damage. The ANSMET project owns some of its own field gear, and team members bring some personal clothing and camping equipment to the field. Unlike space flight hardware, field gear is purposely chosen to be simple, robust, and available from commercial sources and therefore replaceable. ANSMET team members generally do not (and need not) consult anyone besides their colleagues in the field for nominal or off-nominal operations.

ANSMET crew members are selected by the PI from a pool of interested applicants. The PI gives priority to scientists whose research is related to Antarctic meteorites, and who would gain important academic benefits from seeing the environmental settings of the specimens. Because most ANSMET participants are drawn from the relatively small and close-knit community of planetary science, it is possible for the PI to know the applicants personally or by reputation, and to select crew members on that basis. ANSMET team selection is complicated by the short time (about 10 days) available for the team to learn to work together before deploying to the deep field. The PI must compensate by choosing crew members who are likely to get along well together from the start. The PI also ensures team competency by including veteran ANSMET participants in each group.

4.2. Transportation

Ski-equipped Twin Otter aircraft provide responsive transportation for teams in the Antarctic deep field. An ill or injured ANSMET team member can be airlifted to the small medical clinic in McMurdo within 8 h to a few days, depending on weather, aircraft availability, and the severity of the case. For cases beyond the clinic's capabilities, patients can be delivered from McMurdo to hospitals in Christchurch in about 3 days. It is not unusual for one or two team members to enter or leave the field, or to move between the reconnaissance team and the systematic search team, in conjunction with mid-season resupply flights.

4.3. Communication

ANSMET teams carry two or three Iridium satellite telephones for the group to share. Voice calls can be made at any time, but the service is expensive, bandwidth is low, and poor satellite geometry often causes calls to be dropped. The satellite phone can operate as a modem for sending text e-mail and small (< 100 KB) pictures. It can receive 120-character text messages. Each ANSMET team also carries a high-frequency (shortwave) radio set, but it is time-consuming to set up and susceptible to solar interference, and so is used much less than the satellite phones. There is currently no way to send live motion imagery to or from an ANSMET field camp. Antarctic field teams are required to use their communication assets to check in with McMurdo Station at a designated time every day. If the expected check-in call does not come, emergency rescue assets are activated within 3 h. Even with some friendly pleasantries, the daily “all is well” call to Mac Ops may take only a minute or two. Longer discussions are needed only in case of major changes to the field season plan.

Medical conditions arising in an ANSMET field camp that do not require evacuation but that are beyond over-the-counter medications and basic first aid can be treated with direct guidance, via satellite phone, from medical practitioners in McMurdo.

4.4. System control

ANSMET teams operate all their own field equipment. There is no capability for remote commanding, nor is any telemetry transmitted from camp. Most of the equipment is simple to operate, so pre-season instruction such as the snow school trip can serve crew training needs. When hardware does not perform right, ANSMET team members often must use it anyway. When it fails outright, they either do without it or repair it themselves using whatever level of mechanical skills they happen to possess. Although experts in McMurdo may be available for satellite phone consultation during working hours, field repairs are typically done without contacting anyone outside camp. An exception is snowmobile repair. Snowmobiles are critical equipment: a team member with a “down” vehicle cannot effectively search for meteorites. Replacement snowmobiles may be difficult to deliver or completely unavailable. Snowmobile work is therefore often guided by satellite phone discussion with the maintenance shop in McMurdo.

4.5. Logistics

Cargo bound for Antarctic field camps is planned, gathered, and packed by the team members themselves in McMurdo during the 2 weeks preceding their departure for the field. Once the field gear is packed and placed on pallets, cargo handlers further prepare it for aircraft transportation. The field team helps the aircraft loadmaster to unload cargo at the field site. The team members do all their own unpacking and stowage in the field. No outside entity or electronic tool keeps track of where things are in an ANSMET field camp. Typically, containers are labeled with their general contents. The mountaineer or the PI records detailed descriptions of each container's contents in a logbook that accompanies them to the field.

Resupply flights to ANSMET camps may happen weekly (for the reconnaissance team) or twice during the season (for the systematic search team). Team members can request items for resupply, typically a week before the flight. Resupply flight dates are subject to change for weather and aircraft availability, and may arrive earlier or later than planned. Additional flights to deliver critical spares are not generally approved, but it may be possible to get a critical spare onto a planned resupply flight with as little as 24 h notice. Morale items such as mail, fresh food, and cargo specifically designated for resupply by team members are high-priority items for most resupply flights. ANSMET camps keep ~30% reserves of critical consumables (food and stove fuel, the latter needed for warming tents, for cooking, and for melting ice to make drinking water) and a limited selection of spare parts and equipment.

4.6. *Work planning*

The ANSMET PI plans and re-plans all field work. Preseason cargo and transportation plans are made in consultation with USAP logistics coordinators, especially those managing aircraft support. Authorization from higher USAP officials is required for substantial deviations from the plan, especially those involving additional aircraft flights or personnel. For smaller changes, the PI has both the flexibility and the authority to modify the daily work plan based on weather conditions, team status, and the group's progress toward its goals.

5. Discussion

Table 1 summarizes the characteristics of ISS, Mars DRA 5.0, and ANSMET that relate to crew autonomy. Superscript letters mark areas where ANSMET teams are more autonomous than ISS crews and where planners of future deep space exploration missions might look to ANSMET for valuable insights. The indicated areas of interest are mission command; mission monitoring; science leadership; equipment stewardship; communication of text, data, and still imagery; crew operation; system knowledge; failure response; manifesting; stowage; and replanning.

5.1. *Mission command*

The ANSMET PI holds full command authority over the field team. ANSMET provides a model environment for command on a Mars mission, where the control center will still provide a leadership function, but to a lesser degree than on ISS. One subset of crew command where the ANSMET model may be especially valuable is crew tasking. On ISS today, crew members are specifically trained for the tasks they will do on orbit, with limited flexibility for adaptive reassignment during the mission. When reassignment is necessary, the decision is usually made in the control center. Because a Mars mission will have a longer duration and a greater variety of tasks, it will include more changes to pre-planned crew tasking than an ISS expedition. The Mars crew CDR will need the same authority as the ANSMET team leader to make those changes without consulting the ground, especially when there is not enough time for back-and-forth radio calls.

5.2. *Mission monitoring*

The ANSMET PI and the mountaineer jointly monitor the team's progress and make appropriate changes to tasking, schedules, and priorities. On ISS, that function is primarily performed on Earth. On a Mars mission there will be much wasted time and effort if this function is retained in the control center, whose situational awareness is impaired and whose advice is delayed. As in ANSMET, a Mars crew member (probably the CDR) must assume the role of primary monitor for the progress of the team's work, keeping an eye on the clock and the schedule in addition to his or her other tasks.

5.3. *Science leadership*

The ANSMET team leader has full authority to make decisions that affect the scientific return of the mission, a far cry from ISS where all such decisions are made on Earth. In particular, the ANSMET team leader constantly adjusts science tasks and priorities in real time, efficiently responding to unforeseen changes in schedule, weather, terrain, equipment readiness, and other factors. This is the “adaptive-exploratory” approach discussed by Mader et al. [12]. As with mission command and mission monitoring, retaining the scientific leadership function of a Mars flight in a distant control center would be inefficient. Science on Mars must therefore be led by a member of the crew, who might benefit from pre-mission training in an environment like ANSMET. If the overall crew commander and the science leader are not the same person, the boundaries of their respective authority must be clearly defined and exercised in training to prevent conflict.

5.4. *Equipment stewardship*

ANSMET uses equipment owned by the NSF, the ANSMET project itself, and the individual team members. The field team has full responsibility for the use and condition of ANSMET and personal gear, and also some accountability for damage to NSF property. This is in contrast to ISS, where the crew interacts with vehicle systems only according to explicit verbal or written instructions provided by the primary hardware stewards in the control center. On a Mars flight, the crew may have to make decisions and take actions that could potentially damage flight hardware if there is not enough time to consult with the ground. Like ANSMET team members, they will have both more authority to operate mission equipment and more accountability in case of error.

5.5. *Communication of text, data, and still imagery*

On ISS, crews benefit from an essentially unlimited capability to exchange text, data, and still imagery with the ground. On a Mars mission, the bandwidth for such communication will be much smaller. Here again, ANSMET

Table 1
Summary of mission attributes relevant to crew autonomy.

	ISS	ANSMET	Mars
Command			
Mission command[a]	Ground & CDR	PI	CDR & ground
Crew safety leadership	CDR	Mountaineer	CDR
Task prioritization	Ground	PI	Ground
Mission monitoring[a]	Ground prime	PI & mountaineer	CDR prime
Science leadership[a]	Ground	PI	Ground & crew
Equipment stewardship[a]	Ground	NSF & PI	Ground & crew
Crew selection	Agency managers	PI	Agency managers
Transportation			
Medical evacuation	Soyuz return in hours	Twin Otter return in hours to days	None
Communication			
Voice	Near constant	On demand	Limited, delayed
Text and data[a]	Frequent, high bandwidth	On demand, low bandwidth	Limited, delayed
Still imagery[a]	Frequent, high bandwidth	"D/L" only, low bandwidth	Limited, delayed
Motion imagery	Plentiful D/L, U/L possible	No	Limited, delayed
System control			
Crew operation[a]	Infrequent	Crew only	Frequent
Ground operation	Nearly continuous	No	Frequent
System knowledge[a]	Ground prime	Crew prime	Ground prime
Failure response[a]	Ground prime	Crew prime	Ground & crew
Logistics			
Manifesting[a]	Ground	PI	Crew & ground
Packing	Ground	Crew	Ground
Stowage[a]	Ground prime	Crew	Crew & ground
Resupply planning	Ground	PI	None
Critical resupply	Months delay	Days or weeks delay	None
Consumable reserves	Months	1–2 weeks	Limited
Spares	Plentiful	Limited	Limited
Work planning			
Daily planning	Ground	PI	Ground
Replanning[a]	Ground	PI	Crew & ground

[a] Area where ANSMET can provide insight for deep space mission planners (see Section 5).

provides a good model. The limitations imposed by satellite telephone communication force team members and their correspondents to make every transmitted byte count. A well written 120-character text message may be as helpful to a crewmember's morale as a five-page e-mail. A single properly focused, lighted, and framed photograph sent to the ground can eliminate the need to transmit 20 poorly composed ones. Future Mars crews and their correspondents might benefit from communication practice under conditions similar to ANSMET, perhaps using simulated speed-of-light delays for increased realism.

5.6. Crew operation

Core systems aboard the ISS are mostly operated from the control center. Reduced and delayed telemetry from a Mars ship will force many more system operations to be commanded and monitored onboard, either by automated systems or by the crew. Because of the complexity and expense of the former, and the time and workload limits of the latter, tradeoffs are inevitable and both are likely to be used. For operations where the crew is prime, ANSMET offers some insights.

All of the equipment on an ANSMET expedition is operated by the crew themselves. Furthermore, some team members may arrive at McMurdo Station with no expertise or even familiarity with the equipment they will trust their lives to. Training time before deployment to the field is limited to a few lectures and the overnight snow school trip. ANSMET teams manage this skill deficit by including Antarctic veterans (who know what to do and can teach the rookies) and by selecting field equipment that is easy to operate, hard to break, and tolerant of user errors. Crew-operated hardware on a Mars flight should be designed with those three qualities as a priority. This will represent a departure from the norm for much aerospace technology, which can be complicated, fragile, and unforgiving.

5.7. System knowledge

As with system operation, system knowledge for the ISS resides largely on the ground. Even with the current 2.5-year training campaign, ISS crews simply cannot memorize all there is to know about the vehicle's complex core systems. A Mars ship might be similarly complicated. But given the unavoidable delays in getting answers from the control center, a greater share of system knowledge will have to reside onboard. Much of that knowledge will never be needed urgently. It can be in the form of manuals, probably in electronic form to save weight. But even the smaller quantity of system information that might be needed quickly could easily be more than a crewmember can remember. This limitation demands that the ship's systems be made as simple as possible. Antarctic field gear could provide instructive examples.

5.8. Failure response

System operation and system knowledge are closely related to failure response. Today, crews on ISS rarely respond to onboard failures without extensive consultation with the control center. Often the result is a new, customized recovery procedure. The crew is prime only for a small subset of possible failure responses, generally those that require fast action and those that break the communication link with the ground. On a Mars mission, communication limitations will enlarge that subset.

On an ANSMET expedition, the relatively untrained field team is prime for the response to almost all equipment failures, a situation that is perfectly acceptable for three reasons. First, most ANSMET expedition gear has been tested under brutal field conditions for many seasons. Items that break get replaced with something tougher. Second, much ANSMET gear is redundant: if one tent group's solar power unit fails, they can recharge their electronics at their neighbor's. Third, with the notable exception of the snowmobiles, much ANSMET gear can be repaired in the field by an unskilled person using only basic hand tools and freezer tape. Designers of equipment for a Mars expedition should strive for similar robustness, redundancy, and simplicity.

5.9. Manifesting

Except for a very small number of crew-preference items such as clothing and personal mementos, the ground plans and prioritizes all cargo manifests for flights to the ISS. The five-times-longer duration of a Mars expedition will mean more, and more kinds of, crew-preference items will be flown. The crew will play a greater role in defining the cargo manifest. Here ANSMET provides an extreme example. The team leader and the mountaineer choose almost everything that goes into the field: tents, snowmobiles, tools and spares, fuel for vehicles and stoves, paper towels, toilet paper, and a host of other equipment. Each two-person tent group makes its own food selections for the 6-week field season (about 8% of the total deployed equipment mass), and each team member chooses his or her own personal clothing and entertainment items (about 2%). These personal items may include flags, decorations, and other means for non-destructive personalization of field gear, which is encouraged to improve morale and promote team spirit. Individual ANSMET team members also enjoy some latitude to select their USAP-issued equipment, such as clothing, sleeping bags, and cooking utensils, from a range of available items. The freedom to choose those few things, trivial in terms of mass and volume, appears to confer a big psychological benefit for people working in otherwise highly constrained and difficult conditions. With appropriate adjustments for mission duration, a Mars crew might assume the primary role for selecting analogous types and mass fractions of their ship's manifested cargo.

5.10. Stowage

ISS crews and ground controllers invest substantial effort to keep track of where items onboard the vehicle are stowed. Future exploration missions that manage inventory remotely will be further hampered by long communication delays. They would benefit from a more efficient system.

ANSMET suggests possibilities for improvement. ANSMET field teams pack all their own gear for transport to the field, then unload it and stow it in camp themselves. Inventory is tracked with human memory and personal written notes. Although there is an occasional search for a tool or a food packet, serious problems are uncommon. Stowage and retrieval of commonly used items is facilitated by the design of the Scott tent, which includes a row of storage pockets sewn onto the tent's inner wall. Similar pockets could be placed on the interior panels of a spacecraft or habitat, and perhaps improved by fabricating them out of clear plastic so that the contents are easily visible. The ANSMET experience also suggests that stowing items in clear containers, and placing complete, erasable, re-writable content labels on the outside of opaque containers, could further reduce the crew effort needed to stow and find equipment.

5.11. Replanning

On ISS, the control center manages the schedule. On a Mars mission, waiting tens of minutes for the ground to respond to a schedule problem will only make the situation worse. ANSMET teams effectively manage daily schedule changes without interacting with a control center. If the day runs late, the PI decides which tasks will and will not be completed. Mars mission crews will need similar authority. If an electronic schedule is maintained onboard, the crew will need to manage it, preferably using software that does not itself consume much valuable work time.

6. Conclusion

In this paper, we have examined the elements of present-day ISS missions and notional future Mars missions that most relate to crew autonomy. Deep space missions will travel great distances from Earth, which means that communication with the ground control center will be delayed and diminished. This in turn will force the crew to assume some tasks and functions currently performed by the flight control team, while isolating them from the assistance the ground provides to today’s ISS crews. The history of human space flight provides scant guidance for implementing such a high degree of crew autonomy.

For many years, the ANSMET project has sent small teams to Antarctica on expeditions that are analogous to long-duration space flights. ANSMET teams operate successfully without an external control authority. ANSMET can therefore provide planners of future deep-space exploration missions with valuable insights on many aspects of crew autonomy. The ANSMET model both demonstrates the need for, and suggests how to implement, such changes as granting the crew the authority to adjust daily schedules, crew task assignments, and competing work priorities without consulting the control center; enlisting the crew as the primary monitor of mission progress and a more accountable steward of flight hardware; making the most of limited bandwidth for the communication of electronic data; designing equipment simple enough that the crew can knowledgeably operate it and respond to its failures, again without involving the ground; and giving the crew greater voice and more responsibility for the manifesting and stowage of their equipment.

Besides its primary mission of obtaining extraterrestrial samples for scientific study, ANSMET provides the space exploration community with more than just planning insights. Over the years a handful of astronauts have participated in ANSMET and declared it an excellent model for space flight. The authors hope that this mutually beneficial cooperation will continue. Perhaps the crew of a future Mars mission will train together in Antarctica as part of their preparation for flight.

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