THE ROLE OF THE SPACECRAFT OPERATOR IN SCIENTIFIC EXPLORATION. S. G. Love, NASA Johnson Space Center, Mail Code CB, 2101 NASA Parkway, Houston, TX 77058, stanley.g.love@nasa.gov.

Introduction: Human space exploration has primarily focussed on national prestige and engineering development. Accordingly, astronauts have typically been military test pilots and flight engineers. These men and women created the culture and methods of human space flight, which resemble those of aviation.

Following the historical example of Antarctica, future space exploration will likely place science on a par with engineering and national renown. Future crews will include more scientists. This will represent a fundamental cultural change. Piloting and engineering skills will still be important, but they will relate to fewer key mission goals. Meanwhile the scientist's skills--observing, questioning, and forming and testing hypotheses--will move to the forefront. This shift in emphasis raises the question of what the spacecraft pilot or flight engineer (the "operator") should do when the day's work is led by a crewmate (the "scientist") and requires skills in which the operator has less training.

Fortunately, Earth-based space flight analogs currently employ scientists in pairs or teams with astronauts, providing opportunities to define the role of the operator in scientific exploration. This report is based on experience in the 2004-2005 Antarctic Search for Meteorites expedition, the 2010 Desert Research and Technology Studies (Desert RATS) exercise, and the 2010 season of the Pavilion Lake Research Project. It explains to scientists why operators talk and behave as they do, and presents aspects of aviation culture that can improve scientific missions. It is also intended to help operators support scientific field work that they may not understand by contributing leadership, teamwork, communication, and operational thinking skills.

1. Leadership: The danger, fatigue, isolation, and discomfort of an expedition can strain relationships and make cooperation impossible. Few scientists receive leadership training, but an operator versed in aviation Cockpit Resource Management (CRM) and "expeditionary behavior" [1-3] can act as a leadership model.

Helpful concepts from CRM include accepting that errors happen, backing up crewmates' work to trap errors without confrontation or blame, giving feedback to crewmates in a positive way, gracefully admitting errors and seeking and accepting critiques of one's own work and interactions, actively improving one's own skills, conducting prebriefs to clarify expectations for upcoming work and debriefs to recognize technical and teamwork-related results from completed work, and avoiding division among mission personnel. CRM principles suggest that operators in science expeditions learn about the mission's scientific goals, methods, and language so that they can contribute more toward science objectives.

Good expeditionary behavior includes placing team goals before personal goals and the welfare of others equal to one's own; valuing empathy, honesty, diplomacy, selflessness, courtesy, competence, and good judgment; ensuring that basic requirements for food, water, rest, etc. are met; managing one's own condition and limitations; tolerating adversity and uncertainty; helping the team to keep aware of changing conditions and adapt its performance accordingly; completing one's own work and helping others with theirs; speaking when appropriate; listening actively, paraphrasing back, and seeking clarification; enduring and even enjoying challenging work; performing well and staying positive under stress; using appropriate humor; actively contributing to team morale, performance, and goals; effectively managing conflict; cooperating with people from other cultures; and using adaptive leadership styles as appropriate for the situation.

2. Teamwork: An operator can increase the scientific value of a mission by using effective teamwork as tested in Desert RATS, which paired astronauts with geologists for 7-day geological exploration missions. The crews drove a rover between study sites selected by remote sensing and conducted "spacewalks" to obtain imagery and geologic samples at those sites.

During driving traverses, the operator served as crew leader, piloting the vehicle and operating its systems. The scientist supported by running checklists, monitoring the timeline, and cross-checking the operator's work. When not helping the operator, the scientist recorded observations and talked with other scientists by radio. Swapping these roles provided welcome diversity in tasking but impaired science return.

When the vehicle stopped at a study site, the operator safed the rover and prepared suits and tools for the spacewalk while the scientist took context photos and recorded out-the-window observations.

Crews used a third division of labor for efficient work within the strict time limit of a spacewalk. In the field, the most value was added when the scientist was collecting samples and transmitting or recording observations. The operator assisted by offloading as many other tasks from the scientist as possible. These included taking photos; fetching, carrying, and stowing tools; and weighing and measuring samples. When the scientist did not need help or was not nearby, the operator took samples and made basic observations (including sample size, color, texture, and density) that were valuable even without specialized terminology.

Inside the rover after a spacewalk, the scientist took final context photos and recorded his or her impressions of the geology while the operator secured the spacewalk hardware and prepared the rover for travel.

Although future space missions will have different goals and crew compositions, the Desert RATS experience suggests that similar flexibility of leadership and tasking will maximize science return.

3. Communication: If radio communication is good and time allows, unstructured discussions among scientists can add value to an ongoing mission. When the radio link is noisy or time-limited, or when operational or safety-related information must be communicated, the operator's expertise in formal radio techniques becomes more valuable.

Aviation radio protocol [4,5] was developed to provide the best possible understanding with the fewest possible syllables, in an environment where a misunderstood call on a noisy, crowded radio channel can have deadly consequences. The current system is not perfect, but its value has been tested for decades in billions of airplane operations and (with minor adjustments [6,7]) in all NASA piloted space missions. Its features include a structured format for common radio calls; specific times, places, and events when radio reports are required; use of the 24-hour Coordinated Universal Time clock; use of the ICAO phonetic alphabet [4] for spelling out words and numbers; common terminology (e.g., "affirmative," "copy," "say again," "over," etc.); monitoring of signal quality; and allowed use of plain language when standard phrases do not convey meaning well enough.

Good radio calls are phrased so that the receiving party does not have to ask for clarification. They include all relevant information, but do not clutter the channel or waste the listener's time. They state the most critical information first in case the call is cut off prematurely. They use a professional yet friendly tone of voice with no trace of frustration or impatience. They exclude jargon, chatter, profanity, figures of speech, and "CB" slang. They are comprehensible to people who know English as a non-native language. They are assertive enough to transmit needed information, but do not step on calls of higher priority.

Skilled radio operators acknowledge all calls within a few seconds, saying "stand by" if not yet able to give a better response. They anticipate upcoming frequency changes and gaps in the radio link, make plans to re-establish contact when the link is restored, and know what to do if communication is unexpectedly lost. They listen before transmitting, make calls mentally before making them verbally, and after keying the microphone pause for a half-second before speaking so that the first syllable is not cut off.

Another facet of communication is hand signals [3]. These can be useful if radio contact is lost while line of sight remains, or to communicate while keeping the radio channel clear for higher-priority transmissions (such as a scientific field note during a Desert RATS spacewalk). Crews should establish hand signals for simple messages such as "I'm OK, are you?" "I can't transmit," "stop," and "go that way." Familiar scuba-diving and formation-flying signals are good choices.

4. Operational Thinking: This concept is hard to define but critical for success in risky, time-constrained activities. Pilots, flight engineers, and experienced field scientists are trained to think operationally. Others may not be. Operators can contribute their perspective to make a science mission safer and more effective.

Operational thinking means balancing conflicting priorities; making sound decisions despite time pressure and insufficient data; accepting the consequences of those decisions; reacting swiftly and correctly to problems rather than cogitating upon their causes; habitually using checklists and backing up crewmates' work to minimize errors; and attentively managing finite resources such as fuel, oxygen, and especially time. Operational thinkers know the day's plan and anticipate possible delays. They complete work as early as possible in case of later setbacks. If unable to finish one task, they switch to another so they can make progress. They know that their own competence is a critical, limited resource which can be threatened by fatigue and other factors.

A key aspect of operational thinking is situational awareness: monitoring the mission's conditions and progress while dealing with distractions. Situational awareness is easily lost. Airplanes have run out of fuel and crashed while their pilots troubleshot trivial issues. Good operational thinkers maintain situational awareness and use all available resources of information and experience to cross-check their understanding.

References: [1] Harvey M. (1999) *The National Outdoor Leadership School's Wilderness Guide, 2nd ed.*, Simon and Schuster, New York, 268 pp. [2] Expedition Candidate Training Observation Form (NASA Astronaut Office internal document). [3] Extravehicular Activity Standard Operating Procedures, CB-QMS-004 (NASA Astronaut Office internal document). [4] *Aviation Information Manual*, Federal Aviation Administration, U.S. Department of Transportation (online document). [5] *Pilot/Controller Glossary*, Federal Aviation Administration, U.S. Department of Transportation (online document). [6] Capsule Communicator Handbook, CB-QMS-002 (NASA Astronaut Office internal document). [7] *Flight Control Operations Handbook*, JSC-26843, NASA Johnson Space Center, Houston, TX.