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Desert Research and Technology Studies (DRATS) 2010 science operations: Operational approaches and lessons learned for managing science during human planetary surface missions

Dean Eppler
NASA-Johnson Space Center, dean.b.eppler@nasa.gov

Byron Adams
Arizona State University, byron_adams@byu.edu

Doug Archer
NASA-Johnson Space Center

Greg Baiden
Penguin Consulting, Inc.

Adrian Brown
NASA-Ames Research Center

See next page for additional authors

Eppler, Dean; Adams, Byron; Archer, Doug; Baiden, Greg; Brown, Adrian; Carey, William; Cohen, Barbara; Condit, Chris; Evans, Cindy; Fortezzo, Corey; Garry, Brent; Graff, Trevor; Gruener, John; Heldmann, Jennifer; Hodges, Kip; Horz, Friedrich; Hortado, Jose; Hynek, Brian; Isaacson, Peter; Juranek, Catherine; Klaus, Kurt; Kring, David; Lanza, Nina; Lederer, Susan; Lofgren, Gary; Marinova, Margarita; May, Lisa; Meyer, Jonathan; Ming, Doug; Monteleone, Brian; Morisset, Caroline; Noble, Sarah; Rampe, Elizabeth; Rice, James; Schutt, John; Skinner, James; Tewksbury-Christle, Carolyn M.; Tewksbury, Barbara J.; Vaughan, Alicia; Yingst, Aileen; and Young, Kelsey, "Desert Research and Technology Studies (DRATS) 2010 science operations: Operational approaches and lessons learned for managing science during human planetary surface missions" (2013). *U.S. Air Force Research*. 50.
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Authors

Dean Eppler, Byron Adams, Doug Archer, Greg Baiden, Adrian Brown, William Carey, Barbara Cohen, Chris Condit, Cindy Evans, Corey Fortezzo, Brent Garry, Trevor Graff, John Gruener, Jennifer Heldmann, Kip Hodges, Friedrich Horz, Jose Hortado, Brian Hynek, Peter Isaacson, Catherine Juranek, Kurt Klaus, David Kring, Nina Lanza, Susan Lederer, Gary Lofgren, Margarita Marinova, Lisa May, Jonathan Meyer, Doug Ming, Brian Monteleone, Caroline Morisset, Sarah Noble, Elizabeth Rampe, James Rice, John Schutt, James Skinner, Carolyn M. Tewksbury-Christle, Barbara J. Tewksbury, Alicia Vaughan, Aileen Yingst, and Kelsey Young

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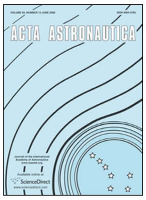

Desert Research and Technology Studies (DRATS) 2010 science operations: Operational approaches and lessons learned for managing science during human planetary surface missions

Dean Eppler[a,*], Byron Adams[k], Doug Archer[a], Greg Baiden[s,t], Adrian Brown[b], William Carey[w], Barbara Cohen[l], Chris Condit[u], Cindy Evans[a], Corey Fortezzo[d], Brent Garry[m], Trevor Graff[a], John Gruener[a], Jennifer Heldmann[b], Kip Hodges[k], Friedrich Hörz[a], Jose Hurtado[h], Brian Hynek[g], Peter Isaacson[j], Catherine Juranek[v], Kurt Klaus[i], David Kring[e], Nina Lanza[n], Susan Lederer[a], Gary Lofgren[a], Margarita Marinova[b], Lisa May[p], Jonathan Meyer[h], Doug Ming[a], Brian Monteleone[k], Caroline Morisset[f], Sarah Noble[c], Elizabeth Rampe[k], James Rice[c], John Schutt[o], James Skinner[d], Carolyn M. Tewksbury-Christle[q], Barbara J. Tewksbury[r], Alicia Vaughan[d], Aileen Yingst[m], Kelsey Young[k]

[a] *NASA-Johnson Space Center, Mail Code KX, 2101 NASA Parkway, Houston, TX 77058, USA*
[b] *NASA-Ames Research Center, USA*
[c] *NASA-Goddard Spaceflight Center, USA*
[d] *U.S. Geological Survey-Flagstaff, USA*
[e] *Lunar and Planetary Institute, USA*
[f] *Canadian Space Agency, Canada*
[g] *University of Colorado, USA*
[h] *University of Texas-El Paso, USA*
[i] *The Boeing Company, Houston, TX, USA*
[j] *Brown University, USA*
[k] *Arizona State University, USA*
[l] *NASA-Marshall Space Flight Center, USA*
[m] *Planetary Science Institute, USA*
[n] *University of New Mexico, USA*
[o] *Antarctic Search for Meteorites Project, USA*
[p] *NASA-Headquarters, USA*
[q] *United States Air Force, USA*
[r] *Hamilton College, USA*
[s] *Penguin Consulting, Inc., Canada*
[t] *Laurentian University, Canada*
[u] *University of Massachusetts-Amherst, USA*
[v] *Northern Arizona University, USA*
[w] *European Space Agency, The Netherlands*

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* Corresponding author. Tel.: +1 281 244 8216; fax: +1 281 483 1573.
E-mail address: dean.b.eppler@nasa.gov (D. Eppler)

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ABSTRACT

Desert Research and Technology Studies (Desert RATS) is a multi-year series of hardware and operations tests carried out annually in the high desert of Arizona on the San Francisco Volcanic Field. These activities are designed to exercise planetary surface hardware and operations in conditions where long-distance, multi-day roving is achievable, and they allow NASA to evaluate different mission concepts and approaches in an environment less costly and more forgiving than space. The results from the RATS tests allow selection of potential operational approaches to planetary surface exploration prior to making commitments to specific flight and mission hardware development. In previous RATS operations, the Science Support Room has operated largely in an advisory role, an approach that was driven by the need to provide a loose science mission framework that would underpin the engineering tests. However, the extensive nature of the traverse operations for 2010 expanded the role of the science operations and tested specific operational approaches. Science mission operations approaches from the Apollo and Mars-Phoenix missions were merged to become the baseline for this test. Six days of traverse operations were conducted during each week of the 2-week test, with three traverse days each week conducted with voice and data communications continuously available, and three traverse days conducted with only two 1-hour communications periods per day. Within this framework, the team evaluated integrated science operations management using real-time, tactical science operations to oversee daily crew activities, and strategic level evaluations of science data and daily traverse results during a post-traverse planning shift. During continuous communications, both tactical and strategic teams were employed. On days when communications were reduced to only two communications periods per day, only a strategic team was employed. The Science Operations Team found that, if communications are good and down-linking of science data is ensured, high quality science returns is possible regardless of communications. What is absent from reduced communications is the scientific interaction between the crew on the planet and the scientists on the ground. These scientific interactions were a critical part of the science process and significantly improved mission science return over reduced communications conditions. The test also showed that the quality of science return is not measurable by simple numerical quantities but is, in fact, based on strongly non-quantifiable factors, such as the interactions between the crew and the Science Operations Teams. Although the metric evaluation data suggested some trends, there was not sufficient granularity in the data or specificity in the metrics to allow those trends to be understood on numerical data alone.

1. Introduction—overview of the Desert RATS 2010 operation

The 2010 Desert RATS test was a 14-day operation conducted at Black Point in the San Francisco Volcanic Field near Flagstaff, AZ, with 2 small-pressurized rover prototypes. Each rover was operated with a 2-person crew consisting of an engineer/commander and a scientist, testing a variety of operations approaches within a scenario of human exploration of the lunar surface (see [1] for a complete description of 2010 and preceding years' RATS missions). Each rover crew conducted a 7-day mission with a mid-mission crew change at the end of Day 7. Mission operations oversight was provided by a Mission Operations Team from the Mission Operations Directorate at Johnson Space Center, which operated out of a remote Mission Control Center (rMCC) located at Black Point Base Camp, and a variety of science operations teams also operating at Black Point and in Flagstaff.

The overarching goal of the test was to operate the rovers under contrasting communications states and modes of rover operations (see Table 1). In order to understand the effects of different communications conditions on science operations, three traverse days each week were conducted with complete voice and data communications available throughout each 24-h day with no delay between transmission and reception (called "Continuous Comm", or CC). The remaining three traverse days simulated operations with two ≈1-h orbital communications satellite passes per day, a condition referred to as twice-a-day comms, or 2/day, that might be in extant during exploration on the lunar far side. In this test case, the assumption was that communications took place every 12 h. In addition to varying communications conditions, rovers were operated either as a mutually supporting team (called "Lead and Follow"), with each rover simultaneously exploring the same terrain, or with each rover in communications contact, but working in different portions of the field area (called "Divide and Conquer"). The testing and communication schedule is delineated in Table 1. In addition to the 12 days of active exploration, 2 days were devoted to operations in a Habitat Demonstration Unit (HDU) Pressurized Excursion Module (PEM) (see [2]).

The Desert RATS 2010 test employed a variety of science operations teams whose task was to manage science operations from support rooms either at the Black Point Base Camp or in Flagstaff, AZ. Selection of the team

Table 1
Desert RATS testing schedule.

Sunday, 29 Aug	Monday, 30 Aug	Tuesday, 31 Aug	Wednesday, 1 Sept	Thursday, 2 Sept	Friday, 3 Sept	Saturday, 4 Sept
Pre-test stand-down	Dry run	Test Begins; CC w/Lead & Follow Ops	CC w/Lead & Follow Ops	CC w/Lead & Follow Ops	2/Day; Divide & Conquer Ops	2/Day; Divide & Conquer Ops
Sunday, 5 Sept	Monday, 6 Sept	Tuesday, 7 Sept	Wednesday, 8 Sept	Thursday, 9 Sept	Friday, 10 Sept	Saturday, 11 Sept
2/Day; Divide & Conquer Ops	PEM Ops; CC	Rover crew change out; CC w/Lead & Follow Ops	CC w/Lead & Follow Ops	CC w/Lead & Follow Ops	2/Day; Divide & Conquer Ops	2/Day; Divide & Conquer Ops
Sunday, 12 Sept	Monday, 13 Sept	Tuesday, 14 Sept	Wednesday, 15 Sept	Thursday, 15 Sept	Friday, 16 Sept	Saturday, 17 Sept
2/Day; Divide & Conquer Ops	PEM Ops; CC	Test ends				

members who would man the Science Support Rooms was a critical decision in that the quality of team would relate directly to the quality of the results. Each team selected was composed of scientists with a background in planetary sciences, and who were at a mix of career levels ranging from graduate students to senior scientists. This selection ensured that each team member would have a background in the science operations conducted by the rover crews and would be better prepared to evaluate the mission. The Science Operations Team consisted of 38 members drawn from 5 NASA Centers, 2 International Partner organizations, 8 universities, and 3 government agencies, and had over 400 years of accumulated experience as scientists working all over the world, including over 37 years of combined geologic fieldwork experience. In addition, professional diversity was equally critical, given the variety of scientific and operational problems encountered. Members of the RATS Science Operations Team had technical backgrounds in geology, planetary science, astronomy, mining engineering, spaceflight operations, mechanical engineering, and experience in such diverse areas as field geology, oil and gas exploration, geophysics, information technology, mining engineering, mine automation and robotics, mineral economics, oceanography, Space Shuttle image analysis, International Space Station research facility development, aerospace engineering, planetary science mission operations, geochemistry, volcanology, impact cratering, igneous petrology, tectonics, and lunar sample analysis. Lastly, experience on space missions was also extensive, with team members having participated in 5 Apollo missions, 2 Mars Exploration Rover missions, 27 Space Shuttle Missions, 6 International Space Station expeditions, NASA-Mir, Stardust, Long-Duration Exposure Facility, Mars Reconnaissance Orbiter, Lunar CRater Observation and Sensing Satellite, Mars-Phoenix, MAVEN, Fermi Gamma Ray Telescope and the BioSAR mission.

Each Science Operations Team was responsible for testing science operations management concepts in concert with the larger mission control team, conducting either real-time, tactical science operations during the day or strategic planning operations conducted at night. Each scientist rotated through several assignments as part of the test. The purpose of this rotation was: (1) to provide exposure to different ground support functions within each team, thus developing a cadre of experienced science support personnel for future NASA missions; and (2) to evaluate the quality of the science operations throughout the test. In particular, exposure to multiple aspects of the operation by each individual was expected to provide a more statistically balanced evaluation of the quality of the operation, and helped eliminate single-point biases that might be introduced with a more limited exposure by each team member.

The purpose of this paper is to document the lessons learned by the Science Operations Team during the course of Desert RATS 2010, in order to apply those lessons to future Desert RATS tests. In addition to the experience of the Science Operations Team, a critical task of the overall RATS 2010 test was to also document the lessons learned from of the rover crews during the conduct of the test. Several papers in this volume, including Love and Bleacher [3]; Bleacher et al. [4]; and, Hurtado et al. [5], summarize the crew experience and the lessons learned by the geologists and astronauts who were serving in the rovers on Desert RATS 2010. Lastly, Bell et al. [6], summarize the lessons learned by the Mission Operations Directorate crew in the rMCC.

2. Science operations management—historical perspectives from crewed and robotic science missions, with applications to the 2010 RATS test

Management of science activities during real-time mission operations has been critical to improving the science return of NASA missions. The Apollo human lunar expeditions and the Mars-Phoenix mission provided contrasting approaches to the science operations management during planetary surface exploration.

2.1. Apollo lunar missions

Although the early Apollo missions were pursued as largely engineering exercises, later Apollo missions concentrated on extensive scientific exploration of the lunar surface. Understanding the nature of surface mission operations during the Apollo missions requires assessment of both the nature of the individual parts and how they were successfully woven together to produce the very synergistic scientific legacy of Apollo Lunar Exploration Program. Years prior to the Apollo 11 landing, it was fully appreciated by science leaders and NASA management that President Kennedy's challenge to the Nation represented an unprecedented opportunity for global scientific leadership and establishing a scientific legacy that would forever change the way in which we understand the origin and evolution of the Earth and planets. This overarching understanding led to the development of significant scientific input to all aspects of the missions, ranging from landing site selection; planning of lunar surface operations and traverses; selection and funding of a wide array of scientific instrumentation to be utilized and deployed both in orbit and on the surface; astronaut selection and training, including astronaut geologic field and classroom training (e.g., [7]); development of new hardware to assist and extend scientific operations (e.g., the Lunar Roving Vehicle); development of new operations techniques to optimize and extend exploration (e.g., Standup EVAs from the LM cabin); field operations training that included astronauts, scientists, mission operations staff and NASA managers working as a team during joint integrated mission simulations in the field; and extensive post-mission debriefings and lessons-learned discussions (see, e.g., Compton [8] or Baldwin [9] for a comprehensive discussion of science planning and execution during Apollo). All of these background activities contributed significantly to successful surface operations on the Moon, but perhaps the most fundamental lesson from the Apollo experience is that optimal planetary surface operations in the future must be based on broad, synergistic foundation of science, astronauts and operations.

The actual landing on the Moon and onset of surface operations was preceded a wide range of activities that developed the partnerships that worked so well during mission operations. Starting soon after their selection, astronauts received geological training in the classroom and on field trips (see, e.g., [7]). When an astronaut was chosen for a particular mission, they participated in the discussions concerning the selection of the landings sites and worked with scientists to familiarize themselves with the choices involved, the scientific goals and objectives and the potential operational challenges (H. Schmitt and J. Head, personal communication, 2009 and 2012). Once sites were selected, astronauts, operations personnel and scientists worked closely together to develop lunar surface exploration traverse plans which were then simulated and tested in field training trips with the prime and backup astronaut crews, the astronauts who would talk with the flight crew on the lunar surface (CAPCOMs), scientists, operations personnel, and mission controllers. These types of close coordination activities developed partnerships, respect, mutual insights and understanding. Scientists understood the complexity of operations and the time constraints of being on the lunar surface, astronauts understood the scientific objectives and how they could accomplish and exceed them, mission operations personnel understood the importance of the scientific objectives and developed insights and new techniques into how they could assist in their accomplishment, and flight control personnel learned how to organize and implement the surface operations in order to optimize the ability to accomplish and exceed the scientific objectives for the mission. Many of these types of simulations, both in the field and in Mission Control in Houston took place before launch. In addition, astronauts, CAPCOMs, traverse planners and scientists had many briefings in the months prior to launch in Houston and at the Kennedy Space Center on details of the specific mission traverses and mission operations. At these meetings, the specific geology of the landing sites, the scientific objectives of the mission, and the implementation of these objectives through a set of pre-planned traverses and sampling operations were reviewed and discussed (J. Head, F. Hörz, personal communication, 2012), and inputs from the astronauts were sought and implemented.

In the conduct of each mission, the purpose of the flight control team that operated out of the Mission Operations Control Room (MOCR) at Johnson Space Center was to manage the time of the crewmembers on the lunar surface in order to meet mission timelines, and evaluate the health and status of the crew and spacecraft in real time, in order to be able to respond to emergencies as soon as possible [13]. During lunar surface operations, the CAPCOMs were scientist-astronauts who had worked extensively with the crew during training and were highly versed in the mission science objectives (W. Phinney, F. Hörz and G. Lofgren, personal communication, 2009 and 2010). Hierarchically below the MOCR positions were a wide variety of back room positions that directly supported the primary flight controllers in the MOCR, including a Field Geology Experiment Support Room. In the case of science support on Apollos 15–17, this Support Room was in turn assisted by an informal group of scientists in a different room who could follow the operations in real time, but who had limited capability to influence operations taking place in the chain of support rooms above them. The most important purpose of these science support teams was to provide the front room controllers with science expertise that, in conjunction with the expertise in science operations developed by the scientist/astronaut/flight control combined team, would make real-time decisions on science operations questions raised on the lunar surface (J. Head, personal communication, 2012).

Each mission developed, prior to launch, a detailed science support plan in order to ensure that mission science objectives were met (e.g., [10–12]). The purpose of these plans were to, "…describe the manner in which the Flight Operations Directorate (FOD) plans to execute the mission control functions for the experiments an integrally related operational objectives assigned…in the Mission Requirements Document [13]." In addition, a stated objective of these plans was to, "attempt to nullify the effects of events perturbing the mission plan and recover nominal mission plan execution conditions [13]," and, "…[to] maximize the capability to move into alternate modes of operation when quick-look data review indicates unusual opportunities exist to maximize science objectives [13].” The pre-planned traverses and individual activities at the stations were designed as a “nominal plan”, but were in no way thought of as a “pre-determined script”. The broad scientific objectives were always kept in mind by the astronauts and the scientists, and it was understood that if new developments occurred during surface operations that could accomplish the objective better than the preplanned activities, than these new objectives clearly had priority and that it was the call of astronaut on the surface as to what to do. For example, the discovery by Dave Scott and Jim Irwin of the “Genesis Rock” (Apollo sample number 15415), the “green glass beads”, and the “Seat Belt basalt” on Apollo 15 clearly called deviation from the nominal plan. Due to the extensive and close pre-mission training and coordination, scientists on the ground had great confidence in the astronauts on the surface to recognize the critical new discoveries and to act accordingly (J. Head, personal communication, 2012). In a similar manner, when operations on the surface deviated from the nominal plan (e.g., time expended extracting the drill on Apollo 15), scientists, engineers and operations personnel on the surface revised the nominal plan while the astronauts on the surface continued their focused operations.

By the time a given Apollo mission was executed, a well-integrated team had developed. Astronauts on the surface conducted scientific analysis and exploration. Mission operations staff and mission controllers maintained seamless operations and monitored hardware behavior in order to optimize the time that the astronauts on the surface had for science and exploration. Scientists monitored the progress of the astronauts on the surface and assessed their scientific descriptions and sample acquisition progress and if necessary, the Science Back Room in the Mission Control Center could provide broad input to the crew through the CAPCOM. However, the scientists were confident in the ability of the crew to identify and respond correctly to new discoveries. The general attitude was, “Let the astronauts do the job they are trained to do and be ready to help when necessary.” Post-EVA debriefs provided the opportunity to give updates and revised traverses, but the exploration of the surface was undertaken by the astronauts, representing the combined Science/Mission Operations Team.

This team effort was the key to mission success in the Apollo Lunar Exploration Program and resulted in its enduring scientific legacy. The lessons learned from this endeavor are: (1) involve all team members together early in the process and build synergism, (2) work together in the scientific training of the astronaut partners so that they can operate on the surface as explorers, not puppets, and (3) stand ready to help at any time during their independent surface operations and exploration, and expect to exchange input between periods of surface activity. Clearly, during longer periods of surface operations on future planetary expeditions, the long time scale of communication will necessitate a significant degree of astronaut independence and autonomy [14]. Thus the Apollo experience may serve as an essential and helpful guide for developing and optimizing this synergism.

2.1.1. *Mars-Phoenix mission*

The Mars-Phoenix Mission was a robotic lander mission that operated on the Martian surface between May and November 2008 [15]. Although not a rover mission, the Mars-Phoenix Mission Team built its operations approach on lessons learned in the Mars Exploration Rover mission [16]. A critical factor in Mars-Phoenix mission operations was managing data return from the surface within a limited return data budget, which drove the Mars-Phoenix team to operate essentially two planning processes: (1) a tactical process that dealt exclusively with those science activities whose commands were up-linked to the spacecraft each Martian day, and (2) a strategic process that considered those science activities that would be executed over the longer planning horizon of the total mission duration [16]. The requirement for teams to operate under different planning horizons was a function of mission duration. In particular, both the MER and Mars-Phoenix missions operated for much longer periods of time than the Apollo missions, and consequently had a much longer time to accomplish mission science operations.

The tactical science operations planning process on Mars-Phoenix determined the specific science data that could be collected within a single Martian day, which was balanced against the spacecraft capabilities, engineering constraints and the daily data up- and down-link limitations of the spacecraft and the Deep Space Network. To that end, a given tactical planning process involved active interplay between engineering constraints and science objectives. Using these constraints and objectives, the tactical planning process generated a series of commands that could be uploaded to the Mars-Phoenix lander in time for execution in the upcoming day (see [16], Table 2, for an excellent graphic on the Mars-Phoenix tactical process).

Bass and Talley [16] defined strategic processes as including, “…the generation of midterm and also long-term ‘strategic’ science plan that describes the possible lander actions from 4 to 11 sols in the future.” Consequently, the strategic science operations process for Mars-Phoenix involved an analysis of high-level science objectives that would be decomposed into more detailed activities. These detailed activities would, in turn, feed the tactical planning process for each day. It is expected that the 2-way communications travel times between targets outside of cis-Lunar space will, in the future, necessitate conducting a strategic science process with human landed missions in a manner similar to Mars-Phoenix, and the 2010 RATS Science Operations Test was designed, in part, to test that process with human exploration crews.

2.1.2. *Application of the Apollo and Mars-Phoenix science Operations processes to the desert RATS 2010 science Operations test*

During pre-mission planning, it became clear that the communications design planned for the mission would allow conversations between Mission Operations Teams at Black Point Base Camp and the crew in the field to occur without any communications delay. This operation

Table 2
Science Data Collection Metric. The individual scores from each sub-area were summed to give the total score. Data collected on Desert RATS 2010 are shown graphically in Figs. 4 through 6.

Rating	Definition	Description
Regional context		
0	None	No geologic context described
1	Limited	Sketchy geologic context described
2	Sufficient	Geologic context described and understood in Science Support Room; in particular, how do the units at this site relate to the units in previous sites
Stratigraphy		
0	None	No stratigraphic relations described
1	Limited	Relationship of stratigraphic units not described
2	Sufficient	Stratigraphic relationships between units described and information understood in the Science Support Room
Stratigraphic sampling		
0	None	No stratigraphic units sampled
1	Limited	Not all stratigraphic units sampled
2	Sufficient	All stratigraphic units sampled
Sample description		
0	None	No sample descriptions
1	Limited	Not all samples were adequately described
2	Sufficient	Samples were sufficiently described and understood in the Science Support Room
Sample collection		
0	None	No Sample numbers and collection boxes described
1	Limited	Not all sample numbers and collection boxes described
2	Sufficient	Samples numbers and collection box designation were sufficiently described and understood by the Science Support Room
Summary		
0–10	Combined score	A maximum score of 10 would mean that all science available science data from a given station had been acquired during the activities at that station

was largely identical to kind of operations carried out on Apollo, which were characterized as "tactical" in nature. Given the length of the planned 2010 mission, it was also clear that assimilating and analyzing the data produced during each day's operations would be an important process for influencing plans on subsequent traverse days. Consequently, the science team decided that in addition to tactical science operations on RATS 2010, the Science Operations Team would conduct a strategic science operation in order to test the efficacy of strategic planning on the conduct of future human planetary surface operations. This test would integrate operations approaches proven to be successful on both human and robotic planetary exploration programs.

3. RATS 2010 science Operations test overview

The objectives for science operations at Desert RATS 2010 were to (1) evaluate operations with two Tactical Science Operations Teams (TSOT), and a Strategic Science Operations Team (SSOT); and (2) evaluate a methodology for measuring science productivity as a function of varying communications conditions. The TSOTs were responsible for managing real-time operations of the crewmembers at each station and assumed operational control of the crewmembers from the Test Director and the Mission Operations Test Team whenever they were off the rovers and conducting exploratory science. During the traverses between stations, the Test Director and the Mission Operations Directorate control team managed the rovers, although all visible images and verbal communications with the crew were available to each TSOT in real time. The SSOT was responsible for evaluating the scientific output of each day's activities and conducting, as necessary, replanning efforts after each day's traverse operations had been completed. Traverses would be replanned based on either science objectives missed or serendipitous science discoveries that potentially would alter mission

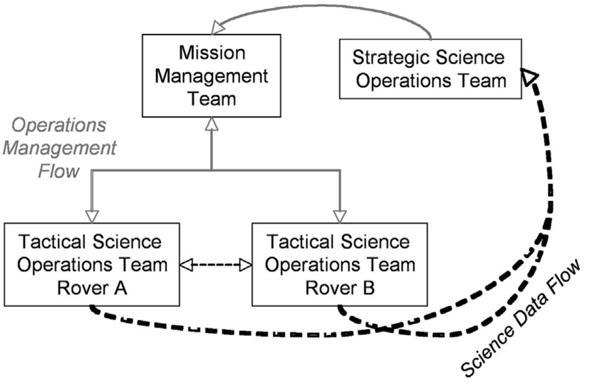

Fig. 1. Science team relationships on Desert RATS 2010. The job of the Field Science Operations Team (FSOT) was to operate as a loss-of-communications backup, and under nominal operations would not have an input into the information flow depicted in this chart. In the event of a loss of communications, the FSOT would assume the responsibilities of the Tactical Science Operations Teams.

science objectives. In addition to the Strategic and Tactical Science Operations Teams, a Field Science Operations Team (FSOT) operated during each traverse day. The FSOT's job was to evaluate crew performance without the filter of the communications net that existed for the other teams. In particular, the FSOT members looked at crew performance on the various geologic tasks as a way of understanding, where necessary, how communications affected the remote Science Operations Team s' perception of science effectiveness. In addition, it was planned that the FSOT would take operational control of the science mission in the field if a major breakdown in communications took place. However, no serious communications failures occurred during the 2010 RATS mission and this function was not tested.

As part of the overall science mission management activity, a designated Mission Lead Scientist participated daily in Mission Management Team (MMT) meetings (see Fig. 1 below), where science results and their potential impact on the overall operation were discussed with the Mission Manager and other team leads, including the Rover Team, the Mission Operations Team and the Astronaut Office representative. The Science Team participated as a full member of the Mission Management Team, and science objectives, as much as engineering objectives, drove decision making throughout the test. In addition to MMT participation, the Mission Lead Scientist debriefed the rover crews at the end of the day, gave a "hand-off" briefing to the SSOT each evening at the start of their shift, and conducted the morning science briefing to the rover crews.

3.1. *Science operations team schedules*

The TSOT operated from 7:00 AM to 5:30 PM each day of continuous communications and PEM operations (see Fig. 2). Each rover had a dedicated TSOT. During 2/Day communications test, the TSOTs stood down from operations. Each member of the team was responsible for a particular segment of the operation, including overall management of daily science objectives, interfacing with the Mission Operations Team, management of sample documentation, collecting data on geologic context, and evaluating data from a variety of cameras and science instruments on the Rovers. The two TSOTs operated out of dedicated Science Support Rooms at Black Point Base Camp.

The SSOT shift began at roughly 8:00 PM, ending when a data analysis and replanning effort was complete. A typical SSOT shift ended at ≈4:00 AM. Each individual on the SSOT was responsible for analyzing a particular science data set and developing an understanding of what was accomplished during the previous day, recommending on the basis of that analysis if any changes needed to be made to the following day's activities.

4. Detailed overview of RATS science team operation

4.1. *Tactical Science Operations Team (TSOT)*

The TSOT had three objectives: (1) evaluate the effectiveness of science data collection during each shift; (2) provide technical assistance to the rover crews during geologic operations; and, (3) evaluate the effectiveness of the science operations setup as implemented for Desert RATS 2010. Each tactical team worked with an assigned rover crew, coordinating with the Test Director to accomplish the daily science plan. In addition, the Science Leads for each TSOT conducted face-to-face tag-ups while rovers were traversing between stations to resolve any issues that arose at a given station.

4.1.1. *TSOT membership*

Each TSOT was staffed with the following team members, who operated console positions in each TSOT:

- Team Lead (SCIENCE)—Responsible for all science operations decisions for a given rover.
- Science Communicator (SCICOM)—Direct voice link with the rover crew; patterned after the CAPCOM position in the higher level test control room, SCICOM was the only Science Support Room person to interact directly with the crew during EVA operations.
- Documentarian—Responsible for maintaining a diary of all science operations, including problems that arose and notable science accomplishments.
- Operations Team Liaison (OPSLINK) (co-located with Test Director)—Responsible for communication "hand-offs" between the Test Director (TD) and the Science Team Lead as well as acting as liaison between teams on any operational issues.
- EV1 Science Lead (EV1) and EV2 Science Lead (EV2)—Responsible for overseeing the science operations of the

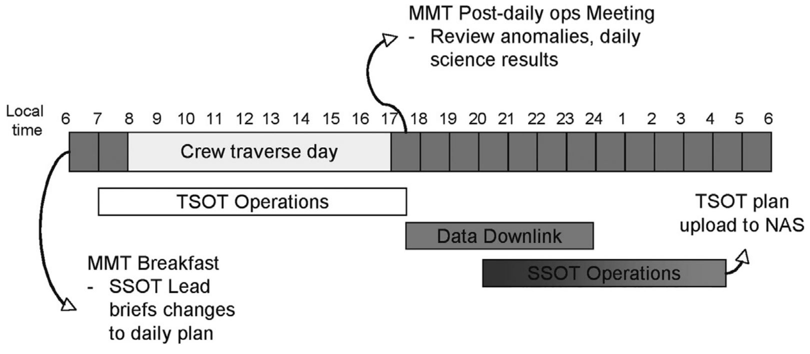

Fig. 2. Daily operations schedule for RATS 2010.

EV1 crewmember, including data captures from EVA system cameras (see Hurtado et al. [5] and Bleacher et al. [4], for specific descriptions of camera assets available to the crew), as well as keeping track of science descriptions while on EVA and assisting the Science Team Lead with science questions arose during EVAs.
- GigaPan Operator (GIGAPAN)—Responsible for initiating data acquisition, download and initial evaluation of image quality from the GigaPan camera system on each rover, and providing an evaluation of the geology of the local rover area to assist the Science Team Lead with real-time science questions during EVA.
- MastCam Operator (MASTCAM)—Responsible for initiating data acquisition, download and initial assessment of image quality from the MastCam camera system on each rover, and providing an evaluation of the geology of the local rover area to assist the Science Team Lead with real-time science questions during EVA.

When a rover crew was working GeoLab operations during PEM operations days, the appropriate TSOT room was used to manage these operations (see Evans et al. [2], for a detailed description of GeoLab design and operations). Data acquisition activities were conducted from the TSOT room using the GEOIMAGE and GEODATA system (see Evans et al. [2]) using available consoles that would otherwise be used for rover operations.

4.1.2. TSOT evaluation of science operations

The TSOTs maintained track of the daily timeline as the mission proceeded, ensuring that the following activities occurred:

- science objectives were met for each mission phase;
- sample documentation data was collected in real time;
- geologic context information was provided by the crewmembers;
- timelines for each station were executed as planned.

Each TSOT member was responsible for evaluating the effectiveness of science activities on RATS 2010 using a daily science score sheet (see Tables 2–5). These forms were designed to evaluate whether the activities performed at a given location were effective at determining geologic context and geologic sample character, evaluating sample documentation procedure, and to help determine the causes of errors when science data collection was less than optimal.

4.2. Strategic Science Operations Team (SSOT)

4.2.1. Team objectives

The Strategic Science Operations Team (SSOT) objectives were to (1) assimilate and synthesize the data collected in the day's activities to determine if planned objectives had been met, or if there were any discoveries in the previous day's traverses that would necessitate replanning efforts for the following day's traverses; (2) conduct traverse replanning; (3) set priorities for downlinked data products for the upcoming tactical process; (4) identify and prioritize samples for further analysis on GeoLab operations days; and, (5) evaluate the quality of science data derived in the field by the rover crews and filtered by the Tactical Science Operations Team.

4.2.2. Team methodology

The SSOT operated in a phased approach: the imaging teams and the individual Rover Science Data Teams reviewed their data sets and prepared recommendations for SSOT Lead and the rest of the team. If replanning of the

Table 3
Science Operations Metric. As with the Science Data Collection Metric, the individual scores from each sub-area were summed to give the total score.

Area rated	Rating	Descriptor	Definition
Operations process	0	Unacceptable	Process does not allow science team to address the posed science questions
	1	Borderline	Process is working but improvements are warranted
	2	Acceptable	Process allows science team to address the posed science questions
Operational roles	0	Unacceptable	Role not required for successful operations, i.e., duplication of efforts among roles.
	1	Borderline	Role required, but improvements are warranted
	2	Acceptable	Role required and no improvements necessary (i.e., work load adequate, etc.)
Science data/ hypotheses tracking	0	Unacceptable	Process does not make sufficient data available to evaluate a given hypothesis
	1	Borderline	Process makes available some data, but many questions remain after a given operation
	2	Acceptable	Process allows sufficient data to clearly evaluate hypotheses
Operational leadership	0	Unacceptable	Leadership inadequate to allow operations team to complete the science mission
	1	Borderline	Leadership provides some assistance to the operations team in completion of the science mission, but team is often unable to complete science mission due to lack of direction
	2	Acceptable	Leadership provides assistance and direction during science operations process; makes it easy for the team to complete the science mission
Operations facilities	0	Unacceptable	Operations team is unable to acquire and process data, and manage the science mission
	1	Borderline	Operations team is able to acquire and process data, and manage the science mission, but with significant difficulty
	2	Acceptable	Operations team is able to acquire and process data, and manage the science mission with no difficulty
Summary	10	Maximum score	Science operations worked flawlessly and no improvements necessary

Table 4
Science Merit Metric.

Rating	Descriptor	Definition
1	Limited	Data does not allow understanding of the scientific context of the field area
2	Adequate	Data reaffirms existing hypotheses and facts
3	Sufficient	Data reaffirms existing hypotheses and facts in new areas or levels of detail
4	Significant	Data potentially elucidates or modifies existing hypotheses in new areas or level of detail
5	Exceptional	Data potentially resolves a major scientific question or highly significant hypothesis
6	Discovery	Data potentially introduces a novel idea or hypothesis

Table 5
Technology/Operations Implementation Metric.

0	Poor	Complete failure of instrumentation or total operator error led to missing or largely incomplete geologic data and/or sample documentation information.
1	Limited	Instrumentation failure or major operator error led to minimal geologic context and sample data available, but not sufficient to establish a large scale understanding of the geologic terrane or sample character.
2	Good	Hardware functioned well and operator technique captured sufficient information to establish large-scale terrane context and outcrop distribution, and established acceptable sample documentation data.
3	Significant	Operator technique captured significant information that enabled critical information capture at the outcrop level as well as establishing broader contextual framework and established acceptable sample documentation data.
4	Exceptional	Operator technique captured information that enabled basic research to be done from the captured images and data without the augmentation of separate sample research. In addition, operator collected acceptable sample documentation data.

following day's activities was called for, the rest of the SSOT participated in this effort in order to be completed by the following morning's uplink briefing. See Fig. 3 for a typical strategic planning process.

4.2.3. SSOT membership

The SSOT was staffed by 10 geoscientists who performed the following functions. Some teams were staffed with multiple individuals, who shifted job assignments as the strategic evaluation and planning process proceeded through a given shift.

- Team Lead—Responsible for management and completion of all activities of the SSOT, including replanning of traverses for the following day's science operations and development of the daily science plan.
- Documentarian—Responsible for keeping a real-time log of all activities that occurred within a given shift.
- Strategic Operations Lead—Responsible for managing long-term operational constraints that affected the daily replanning process, including communications constraints, long-term mission objectives, and consumables constraints.
- Activity Planners—Responsible for preparing the revised daily plan for each rover crew based on the recommendations of the SSOT Lead.
- Long-Term Planning Lead—Responsible for (1) coordinating science team groups working on datasets that were critical to planning the next day's tactical activities; (2) determining whether there were any critical discoveries that warranted further study; (3) determining whether there were any issues that would pose a continuing threat to achievement of mission science objectives; (4) revising the traverse plans; and, (5) leading the end-of-day science discussion.
- Geology Team—Responsible for analyzing the data set produced by the Rover imaging and science teams, and making specific recommendations to the Strategic Operations Lead on revising the following day's geologic traverses.
- Mineralogy/Petrology Team—Responsible for analyzing the data set produced by the Rover imaging and science teams, making specific recommendations to the Strategic Operations Lead on revising the following day's geologic traverses, maintaining sample prioritization, and identifying key samples for further analysis on PEM days.
- Rover Imagery Data Team—Responsible for assimilating the data sets from each rover team from a given day and preparing a summary of results, including (1) key results; and, (2) specific key images that illustrated operations during the day's traverse activities.
- GigaPan Data Team—Responsible for reviewing the previous days GigaPan imagery data and preparing a summary for the SSOT of (1) the images from each traverse station; and, (2) specific key images that illustrated the accomplishments at a given traverse station.
- Rover Science Data Team—Responsible for assimilating specific geologic data to prepare a summary for the SSOT of that day's science accomplishments, including (1) selecting key images and science results for presentation to the traverse planners; (2) assessing completion or non-completion of day's plan; (3) identifying "broke points" or areas of unusual accomplishments that might affect the following day's plan; and, (4) keeping a log of all samples collected, including sample description, critical curation data, and an assessment of what samples warrant further studying in the PEM.

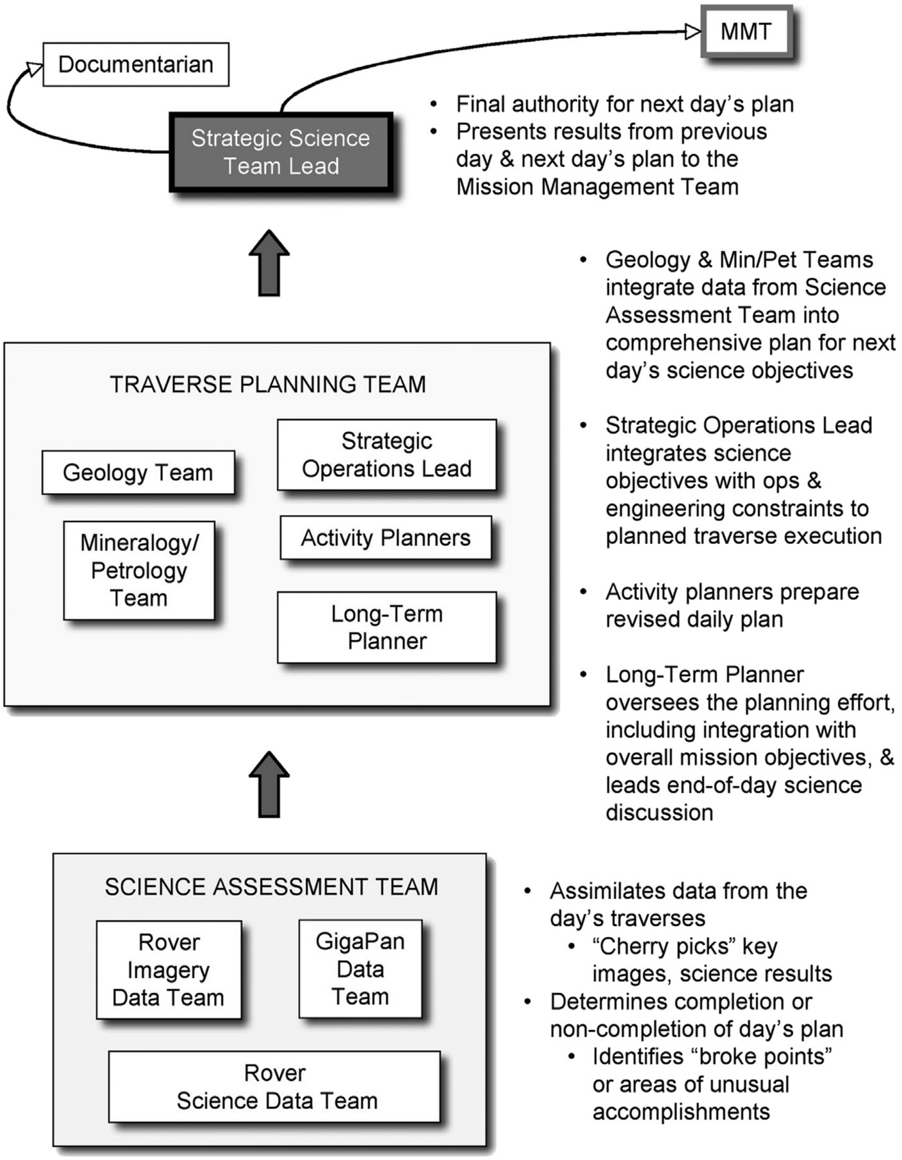

Fig. 3. Strategic Science Operations Team process.

4.2.4. *Schedule*

SSOT daily operations commenced after the end of the day's traverse operations, when the data from the imaging systems and voice communications were downloaded and delivered to the Embassy Suites Conference Facility. Initial assimilation of data took ≈ 4 h. At the end of the assimilation phase, the SSOT Lead determined whether the following day's activities needed to be modified. When modification was called for, the team prepared a revised traverse plan that would be briefed to the Test Director prior to the following morning's uplink briefing to the rover crew (see Figs. 2 and 3). The objectives of critical team meetings are described below.

4.2.4.1. SSOT Kick-off Meeting. During the SSOT Daily Kick-off Meeting, the SSOT Lead provided a brief overview of (1) the present current mission success criteria status and planned objectives for the day just completed; (2) reviewed and prioritized downlinked data sets expected; (3) presented resource estimates for the following day's planned activities (communication schedule, data volumes [critical and non-critical], and total rover operation time; (4) presented any mission updates from MMT; (5) outlined the meeting schedule for shift activities.

4.2.4.2. Science Assessment Team hand-off to Traverse Planning Team. The Science Assessment Team consisted of the Rover Imagery Data Team (see Fig. 3), the GigaPan Data Team and the Rover Science Data Teams. Their job was to assimilate data from the previous day's traverse and prepare a detailed summary of the day's operations. Once the Science Assessment Team completed the review and collation of the previous day's downlinked data, it handed off data products to the Traverse Planning Team to be considered by a combined SSOT Team meeting. This meeting discussed (1) key science data from the day's activities; (2) assessment of completion status of each science objective from the day's activities; and, (3) identification of key events, including either issues that prevented completion of planned science objectives or key, unexpected science results that might merit further study on the following day.

4.2.4.3. Science Activity Plan Approval Meeting. At the completion of each Traverse Planning Team activity, the Long-Term Planning Lead presented the proposed traverse plan for the next day to the SSOT. This meeting was run as a free and open discussion of the proposed plan for the next day's science activities. At the end of the meeting, the SSOT Lead either approved the plan or indicated areas where further replanning efforts were needed prior to presentation to the MMT.

4.2.5. SSOT evaluation of science operations

As with the TSOTs, each SSOT member was responsible for evaluating the effectiveness of science activities on RATS 2010 using an identical daily science score sheet. During continuous communications days, SSOT evaluations added to the data set provided by the TSOT, with the different perspective of making the evaluations on the basis of recorded data that was several hours old. The SSOT was concerned with determining:

- If science objectives were met for each mission phase
- The quality of the downlinked datasets
- If sample documentation data was collected
- If geologic context information was provided by the crewmembers

4.3. Field Science Operations Team (FSOT)

The Field Science Operations Team was responsible for operating in the field with the rover crews, assessing the operation at each field locality that a particular Rover crew investigated.

4.3.1. Team objectives

The objective of the FSOT was to provide on-site evaluations of the crews' observations and sample selections relative to the actual geology present at any given site. They monitored compliance with existing sampling protocols and associated photo documentation, and also judged the crew's performance during communication outages to evaluate the effectiveness of the Tactical Team in supporting the field activities.

4.3.2. Team methodology

Each FSOT consisted of a 2-person team that evaluated how each crewmember conducted their EVA science operations. Each team accompanied a rover during all traverse science operations. The emphasis was on understanding, at the "receiver end", how both communications and operations approaches affected the science being done in the field. In particular, it was critical for each science team evaluator to decide the degree to which the science data collection conducted in the field was being affected, either in a positive or negative sense, by the communications or operational scenario in effect. The FSOT did not interact with the crew in the field, but acted as the Science Operations Team 's eyes and ears on the ground, particularly in situations where communications were compromised. In addition, the FSOT was tasked with assuming the management of science operations in the field if a significant loss of communication between the crew and the TSOT, caused by an unexpected event such as weather or major equipment malfunction, prevented continuation of the nominal mission for periods in excess of minutes. In this role, the field team kept track of timelines and the progress of operations, particularly during traverse stops, to fill in the role that would normally be undertaken by the SCICOM at a particular traverse station.

5. Evaluation of Desert RATS 2010 science operations

A critical aspect of the Desert RATS 2010 test was evaluating the quality of the science return during the mission as a function of variable communications conditions. This evaluation was considered a high priority by both the Science Operations Team and the overall mission management. It was hoped that a clear understanding of the factors that affect the quality of the science return would assist in major architectural decisions for future planetary surface missions.

In order to make this evaluation, the Science Operations Team attempted to use parameters that were either measurable or could be used unambiguously to evaluate the achievement of a particular goal. To that end, a series of science operations evaluation sheets were prepared and filled out by science team members on each Science Operations Team (TSOT, SSOT and FSOT) daily at the completion of a particular operations shift. These evaluation sheets are shown in Tables 2 through 5. In addition to the numerical metrics, each evaluation included written comments on the particular parameter being measured, whether it related to geologic data or the overall operations set up. Evaluations involving fatigue, workload and working conditions were also completed at the beginning, middle and end of a shift.

5.1. Evaluating science merit—consideration of numerical metrics design and data collection

As NASA budgets have come under increasing pressure, the effort to understand the effectiveness of different planetary exploration approaches has led to the collecting of numerical metrics on a variety of test parameters. This effort is reasonable and laudable; in particular, unambiguous, properly collected numerical test data can help make decisions, save development time, and settle differences between devotees of conflicting approaches. A problem arises, however, when numerical metrics are collected on activities that are subjective and non-numerical, such as measuring science productivity or scientific efficiency. Failure to understand both the mathematical basis of a particular evaluation and the legitimate mathematical operations can be carried out on a particular data set can lead to misunderstanding of the importance of a given activity or, worse, lead to incorrect programmatic decisions made on the basis of poorly understood test results.

In many cases, it is valid to use numerical values to evaluate a particular science task. When conducting statistical analyses of a particular parameter, such as the radiometric ages of a given rock unit, more measurements of the sample's age allows definition of the accuracy of the resultant measurement. However, metrics collected by assigning numerical designators to a given characteristic have an underlying assumption that the assigned value is, in fact, a number that has an absolute quantitative value and can be used in the statistical manipulation of study results. Problems arise if this assumption is incorrect. Stevens [17], Lord [18] and Gass [19] have discussed the pitfalls of conducting numerical rankings without having a clear understanding of the numerical character of the qualities being ranked.

Stevens [17] distinguished between cases where (1) a number is a title, such as a designator of a player in a sport (Nominal Scale); (2) rank ordering of different objects or events using a parameter that can establish order but does not define a well-ordered, regular numerical difference, such as the results of a horse race (Ordinal Scale); (3) scales where there is a uniform interval between individual members of a set, but where the set interval is not defined in an absolute sense, such as the Celsius temperature scale (Interval Scale); and, (4) scales where the measurement is a ratio between an absolute zero quantity and a unit scale length, such as the Kelvin temperature scale (Ratio Scale). The critical consideration in all these scales is that while each represents numerical data, statistical manipulation of the data must be based on the kind of data collected. Statistical manipulation of nominal or ordinal data beyond finding the mode, median, percentile and Chi-square, is meaningless. Consequently, it is important to understand the type of numerical scale used for metric data collected in tests such as Desert RATS before statistical manipulations of the resulting data set are carried out and conclusions reached as to the quality or efficacy of a particular approach. Ultimately, numerical data *can* be collected on many aspects of scientific research in a given discipline, but the measurement approaches *must* be fully consistent with the discipline being studied. Failure to understand the nature of a given scientific discipline can lead to the collection of metric data that is flawed, and can, in turn, miss what is important scientifically and what is not.

5.2. *Desert RATS science metrics collection*

The Science Operations Team collected metric data on four separate areas: Science Data Collection (Table 2), Science Operations (Table 3), Science Merit (Table 4) and Technology/Operations Implementation (Table 5). The measurements collected were the result of long discussions within the Desert RATS Team about the specifics of metrics collection, and at the start of the operation, it was felt that the designed metrics had a reasonable chance to successfully discriminate differences between test states. In particular, it was hoped that these metrics would help settle a long-standing debate about whether crews on a planetary body would conduct better science operations under continuous two-way communications or with reduced 2/Day communications conditions.

Ultimately, the results of the numerical data collection were disappointing in that the metric data alone rarely indicated more than general trends, and did not provide sufficient detail to allow the Science Operations Team to understand the underlying factors that contributed to those trends. Although analysis is on going, the authors feel that the design of the numerical metrics was inadvertently flawed for a variety of reasons (the raw metric data is available from the Corresponding Author on request). The discussion below of one metric illustrates the problems we have encountered in post-test analysis of the data.

5.2.1. *Science Data Collection Metric data example: preliminary results and limitations*

The Science Data Collection Metric was used to rate the quality of the geological data collected by each crewmember when conducting traverses in the form of either observations of geologic context or samples (Table 2). This metric required team members from both the TSOT, the SSOT and the FSOT to score a variety of activities carried out by crew during the geological characterization of each field station (see Hörz (2012, this volume), for the specifics on traverse design). Further, a total score for Science Data Collection Metric was created by summing the scores of each of the five individual activity areas. The TSOT conducted the ratings in real-time after the crew completed their station tasks, while the SSOT rated their performance each night after a review of the down-linked voice, video and electronic still image data.

The data set for the Science Data Collection Metric is plotted as a function of geological field station in Figs. 4 through 6. Prior to the start of Desert RATS 2010, it was expected that interaction between the crew and the TSOT during continuous communications would eliminate, or at least greatly reduce, mistakes or omissions, resulting in generally high scores for this metric. It was further expected that high TSOT scores would be mirrored by similar scores from the SSOT. During 2/Day communications, the TSOT would not be in a position to correct these kinds of procedural mistakes, and it was hypothesized that the metric scores would be lower for the SSOT, given that crew operations would have not any real-time Science Operations Team oversight.

The data sets presented in Figs. 4 through 6 illustrate the difficulty the science team encountered in post-mission data analysis, and two issues became clear during post-test data compilation. First, individual scores clustered toward the highest score (see Fig. 4), with only limited values <2. This lack of granularity between highest and lowest scores made it impossible to draw any meaningful conclusions about the

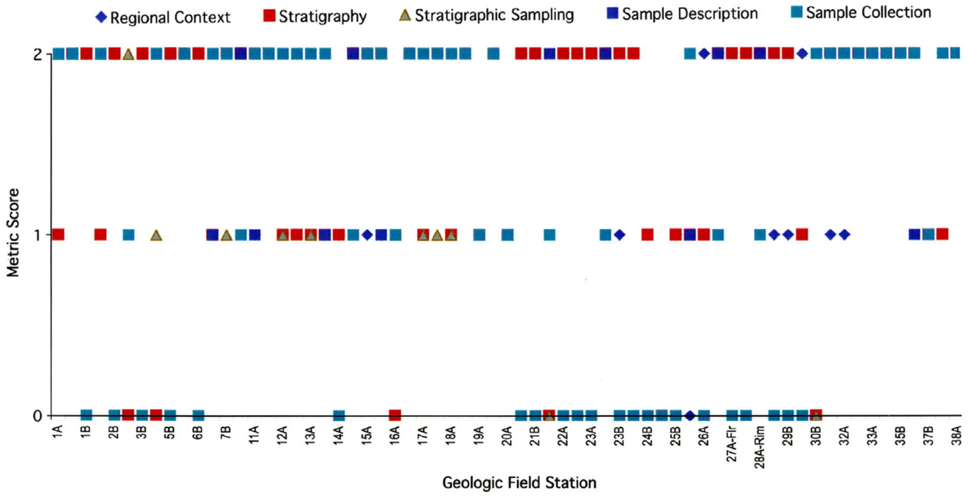

Fig. 4. Strategic Science Operations Team Science Data Collection Metric data for individual sub-categories. The data consists of 65 data points collected throughout the Desert RATS 2010 test (see Table 2 for definition of evaluation criteria). Note the significant overlapping of data at the highest score.

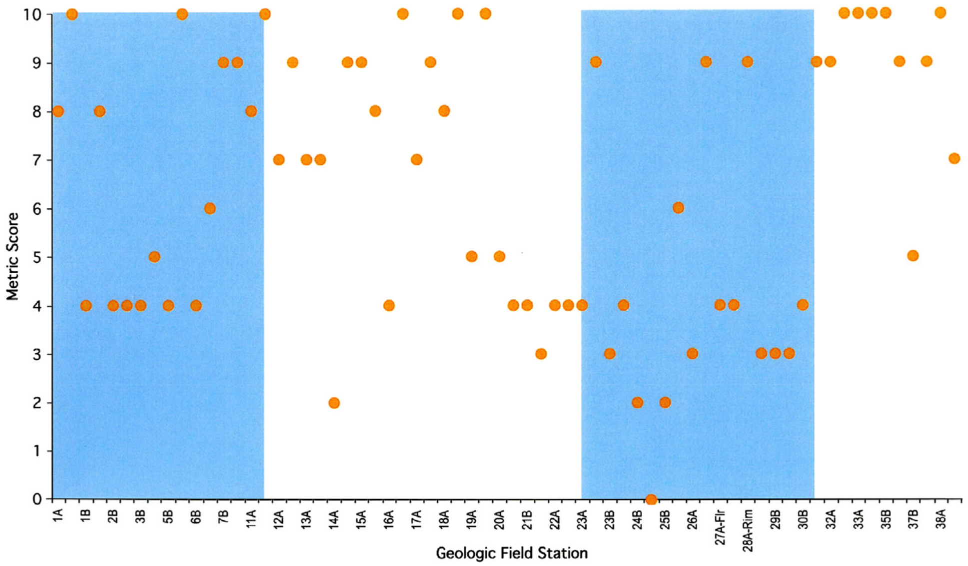

Fig. 5. Strategic Science Operations Team Science Data Collection Metric data combined score. The data consists of 65 data points collected throughout the Desert RATS 2010 test (see Table 2 for definition of evaluation criteria). Blue boxes denote periods of continuous communications.

quality of the individual operations conducted. In particular, it was impossible, on the basis of the raw individual activity scores, to determine if there were any flaws in the field operation that could be corrected in future field tests.

The second issue is that the combined metric scores plotted as a function of field location for both teams indicates a general trend toward higher scores from the TSOT (Fig. 5) on days with continuous communications as compared with the SSOT scores (Fig. 6) on the same days. Given that operations with continuous communications should have provided the highest quality science data for the SSOT to analyze, high SSOT scores would be expected during continuous communications. This was not observed. Further, SSOT scores during 2/day communication days when the TSOT was not operating were generally higher, and the implying better science quality than SSOT scores during continuous communications days. In comparison, metric data collected by the Field Science Operations Teams during the whole test indicate a generally constant level of performance of the crew in the field, regardless of communications state (Fig. 6).

The overall data set implies that the variation in metric scores between the TSOT and SSOT were influenced by factors other than communications state. In short, the hypothesis that science data quality would be controlled solely by communications state was found to

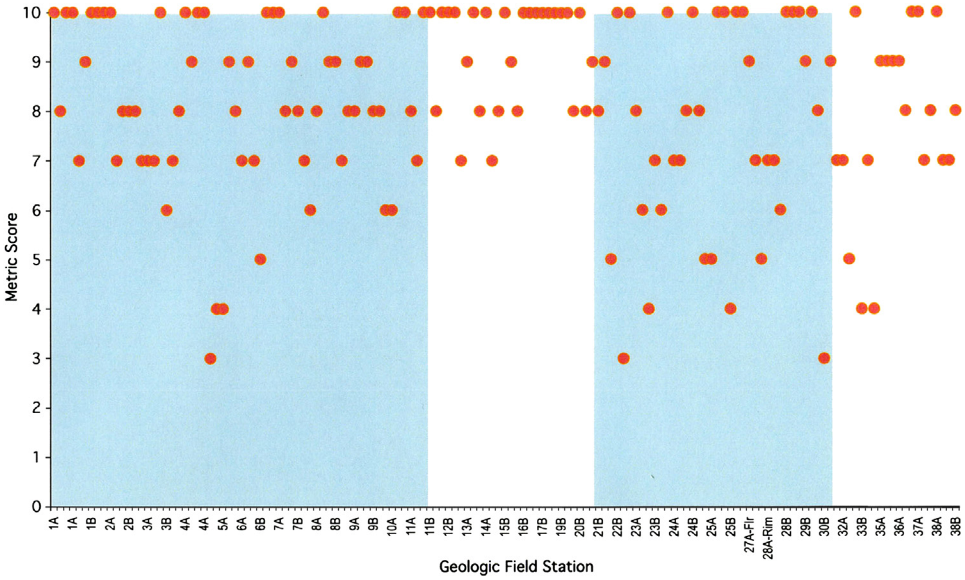

Fig. 6. Tactical Science and Field Science Operations Team Science Data Collection Metric data combined score. The data consists of 146 data points collected throughout the Desert RATS 2010 test (see Table 2 for definition of evaluation criteria). Blue boxes denote periods of continuous communications. During 2/day communications periods, the only tactical assets operating were the Field Science Operations Team.

be not valid, given the consistency of metric scores from the FSOT. It is likely that some component of the interaction between the TSOT and the crew introduced a bias in the data set that affected the SSOT scores, but the pure numerical metrics do not provide insight into the root cause of the difference in scores. Written comments by Science Operations Team members, discussed below, provides better insight into the factors affecting science team operations but so far, no single factor has been identified that directly affects the quality of science return on Desert RATS 2010. Written comments by SSOT members indicated that the volume of data to be analyzed on any given traverse day was extremely large, cumbersome to assimilate and of a highly variable nature, making it difficult to adequately analyze all the data during a given 8-h shift (see Section 6.6). It is not clear how any element of the TSOT process could have affected this condition and led to the variation in metric scores. Additional written comments by SSOT members also indicate that the practice of placing team members into many different jobs during the course of the 2-week test may have introduced significant inefficiency into the data analysis process, but again, it is unclear how this would affect the metric scores. Consequently, it is possible that these scores are related less to crew performance or communications state and more to lack of job experience in the Science Operations Team members on any given day.

Although the data set from the Science Data Collection Metric provided the most obvious example of this disconnect between numerical scores and test conditions, the team experienced similar problems with other metric data sets. A critical lesson learned in the process of collecting science metrics is that numerical data alone do not allow an understanding of the root causes of variations in metric scores.

6. Overall lessons learned

6.1. Team composition and qualifications

The professional experience of the Science Operations Team is critical. In particular, the team cannot be made up exclusively of either non-scientists or junior scientists with little experience. As delineated above, the RATS Science Operations Team was extremely diverse in experience, age and science background. Having an experience level consistent with the mission goals applies to the rover crews as well. Desert RATS 2010 was the first such integrated test where science crewmembers were specifically selected for their abilities and breadth of experience as field geologists.[1] In addition, the astronauts that completed each rover team had, as a minimum, specific training in sampling protocols, and the astronaut team included one individual with advanced degrees in planetary science. Consequently, each rover team had a breadth of science training that exceeded previous years' crews.

6.2. Communications state

6.2.1. Continuous communications

In continuous communications with stable, high fidelity voice and image data, the quality of the overall science is better than communications states where communications are intermittent or have long intervals between contacts. This is a function of the ability of the science team to interact with the crewmembers on the outcrop, in real time,

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[1] In the early years of the Desert RATS series, test subjects were selected for geologic field experience, but those tests were devoted solely to 1–2 h duration pressure garment tests and not multi-day, integrated tests. See Ross et al. [1] for more details.

and science return was greatly improved by that interaction, which was not available on 2-a-day communications. The nature of this interaction was primarily the scientific discussions that were held between the rover crew in the field and the TSOT supporting them. The Science Operations Team member supporting one of the crewmembers on EVA noted, “When all systems were working properly, we got really good data (TSOT A, EVA Science Controller (ES) 2, Mission Day 1, Technology and Operator Performance Metric Database)”. Another science team member noted, “The EVA process worked very well. Again, an educated crew following proper protocol provided sufficient data for science to determine overall regional context and general site geology. EVA Crewmember 1 (EV1) and EVA Crewmember 2 (EV2) have become very adept at communicating with SCICOM and each other without voices running over each other (TSOT B, Science Communicator (SCICOM), Flight Day 2, Science Operations Metric Database).” As it was during the Apollo Program, the crewmembers on the planet's surface are members of a larger science team, and team interaction in science always improves the quality of the final product. However, communications will not always be stable, but a diligent TSOT and a well-trained, scientifically competent astronaut crew can develop methods to work around ratty or intermittent communications, particularly when bad communications are expected. It was noted, “Limited communications today during first EVA led to decision to brief crew prior to and following their EVA. The outcome appears to be very good, and demonstrates that science objectives can still be met under such constrained operations…requires well-trained crew and Science Operations team. Involving science team members in operational roles allows team members to fully appreciate operational constraints. [This is] better than having science team as just advisors/observers of the ops. (TSOT B, ES2, Mission Day 3, Technology and Operator Performance Metric Database).”

With bad communications during the continuous communications phase, science return was limited and led to a loss of critical science data, such as sample documentation and geologic context. It was noted that, “[The] process is working when comm is working. We are unable to evaluate the ability of the crew to address all questions without adequate communication for much of the day…Questions remain about details of outcrop and sample descriptions due to comm limitations. (TSOT B, Documentarian, Mission Day 9, Science Operations Metric Database).”

6.2.2. 2/Day communications

During 2/Day communications state, science analysis and return was directly related to how well the crew gathered the image data and provided the verbal context for that data. Poor imaging system deployment, missed or poorly aligned backpack photographs, and poor or missing crew field notes or missed science objectives resulted in degraded science return. In short, 2/Day communications state requires crewmembers to do the appropriate imaging data runs correctly each time, as the SSOT will not see the final image products until after it is no longer possible to re-occupy a given station. One comment noted, “Unclear context—crew never noted if they were sampling bf1 and bf2 or just one or the other (Strategic Team, Long Term Planner, Mission Day 4, Science Merit Metric Database).”

However, when the rover crew and the systems all worked well, the science data collected was as good as what was achieved during continuous communications. For example, one SSOT member noted, “Crew members did a great job of capturing stills at their sites. EV2's final thoughts at this stop with the HiDEF video imagery were particularly helpful for context (Strategic Team, Geological Data Evaluator (GeoData), Mission Day 4, Technology and Operator Performance Metric Database).”

6.3. *Operations team interactions*

The TSOTs undertook detailed scientific discussions in real time to test science hypotheses, and to decide subsequent courses of action by the crew to improve the science return from the field. These science discussions were a critical part of the TSOT process and mission science, and were independent of communications delay. They were critical to improving science return, and have formed an important part of every human and robotic mission NASA has ever flown. In particular, one TSOT member noted, “When we had communications today we were able to formulate hypotheses in real time along with the crew and provide guidance to them prior to EVAs to look for specific evidence or specific samples to test those hypotheses (TSOT A, ES2, Mission Day 2, Science Operations Metric Database).”

The TSOTs, the SSOT and the Mission Operations Directorate team were able to mesh together as a team and work well together in spite of limited pre-mission time for mutual training and familiarization. This speaks well for the commitment of all members of the team to accomplish the science tasks in spite of limited training and opportunities to work together prior to assembling in Arizona. It was also a critical component of mission operations, as the Science Operations Team on any mission is only one facet of the overall mission. In particular, if the Science Operations Team cannot work effectively with the Mission Operations Team, then effective science return becomes much more difficult. It was noted that, “The ops folks did a pretty good job of keeping us informed when there were issues which allowed us to make decisions and re-plan in real time to get the best science…They were responsive when we informed them of issues (TSOT A, ES2, Mission Day 1, Science Operations Metric Database).”

One area that was not managed well, largely because its value was not understood prior to the RATS 2010 exercise, was the need for hand-off briefings between all elements of the mission management structure on both 2/day and continuous communication days. Hand-off debriefs between the TSOT leads and the SSOT lead at the beginning of a given shift during continuous communication days ensures all science personnel have the same information on critical “on-the-fly” lessons learned and daily science accomplishments. During 2/Day communications days, it was equally critical to conduct quality briefs of the crew in the morning and debriefs of the crew in the afternoon. This ensures that the crew understands science lessons learned from the previous day and the critical activities in the upcoming day, as well as making sure that the SSOT understands, at the end of a particular day, the science results that stood out as well as the lessons learned and science accomplishments that should receive particular attention during the subsequent SSOT session.

6.4. Science team leadership

Good science operations team leadership is crucial for success. If the leadership is good, it can help smooth out problems and make decisions that help the team members proceed, even in the absence of fully functioning systems. Both the TSOTs and the SSOT benefited from good leadership throughout the test. In particular, the team leads made sure that each team member understood the daily mission, and what was expected of them throughout the day. It was noted that, "The tasks of the science ops team were clearly outlined at the beginning of the session, together with the goals of the session itself. Timeliness of the work was also stressed and reiterated throughout (SSOT, ES1, Mission Day 5, Science Operations Metric Database)."

6.5. Numerical metrics on science quality

As discussed in Section 5, the science metrics collected on Desert RATS 2010 did not provide unambiguous answers to the architectural questions this test hoped to address. This may largely be a problem in test design, which was undertaken by science team members versed in the science operations planning but having no professional expertise in designing and implementing these kinds of evaluations. It argues strongly that the numerical metric data collection process must be based on measurement systems designed by professionals in operations research, working in conjunction with the scientists who understand the science operations to be conducted.

A larger issue with the collection of numerical metrics is that science return is more than the statistics of boots-on-the-ground time, samples collected or sites occupied. Science return is the understanding of the geology of a given planet achieved through interaction between the scientists on the crew and the scientists on the ground, and this is not easily measured on the basis of numerical data alone. Without an understanding of the critical interaction between scientists in the process of collecting data and testing ideas, pure numerical data will be unable to provide a clear understanding of the reason for a particular numerical score.

6.6. Training and changes in work assignments

Early on in the plan for Desert RATS 2010, it was decided that science team members would be shifted among a number of job assignments every 3 days. The rationale behind this was both the desire to get as much training for the individual scientists, and to increase the number of people making inputs to the metrics database from a given position. In particular, it was hoped that switching jobs would eliminate any bias within the metric database and improve the effectiveness of the data collection. However, the practice of moving people to new jobs every 3 days meant that no one was in a position long enough to know their jobs well. Consequently, metric data may not represent a "steady state" condition, but in fact may only be quantifying team members' inexperience. One team member noted, "…training has been largely trial by fire, which has its limitations (TSOT A, Mast Camera Data Evaluator (MastCam), Mission Day 9, Science Operations Metric Database)."

6.7. Data analysis activities in support of strategic science operations

The enormous volume of data coming out of any given day of this mission was difficult to review, assimilate, and evaluate the data by the SSOT in the planned 8-h shift. This was partly a problem of data volume, and partly a problem of inefficient manipulation and mining of data sets. In particular, the tools available to the SSOT members were insufficient to allow the SSOT to evaluate the data volumes produced during daily operations, and metrics collected on SSOT operations were subsequently flawed. One SSOT member noted, "I spent over 4 h trying to translate the video/audio and consequently was not ready for the assessment meeting. We could really use a software program that translates the audio into a typed format for our review; it would allow hours more time for interpretation of data (SSOT, GeoData, Flight Day 5, Technology and Operator Performance Metric Database)."

In particular, the trends in the Science Data Collection Metric discussed in Section 5 may be related to inefficient and frustrating data mining and analysis techniques imposed on the SSOT. Two possible ideas may be considered: first, when comparing SSOT to TSOT operations, the real-time assessment, integration and discussion conducted by the TSOTs during the course of a day may have given the TSOT a better understanding of the geology than was possible for the SSOT to achieve during an 8-h shift. Alternatively, the higher metric scores recorded by the SSOT during 2/Day communications may represent decreases in SSOT frustration when analyzing data sets unencumbered by the additional TSOT data that was added to the databases during continuous communications conditions.

One additional consideration with regards to science data analysis during the mission lies in the issue of what was really needed. The SSOT based its task on an initial assessment of all the data that was available, which led to the problems detailed above. Part of the future pre-mission planning should be to consider, in consult between the science planners and the Mission Operations Team, what data will be needed to make the kinds of real-time operations decisions, and to design the data systems to make that data easier to extract.

7. Suggestions for improvement

Desert RATS 2010 was a successful test, in that it integrated science operations concepts from both human and robotic planetary surface missions. However, there were important issues uncovered during the conduct of the test that should be addressed prior to conducting similar operations in the future. The suggestions to improve future operations gleaned from this test can be summarized as follows:

- If collection of numerical metrics is going to be an activity in this kind of test, individuals with an operational research background must be engaged to help design better metrics than those employed this year.
- Qualitative comments by team members will be as critical to improving science operations as the quantitative metrics. In particular, the ability to effectively and consistently capture qualitative evaluations must be a critical part of the test evaluation protocol.
- Krikalev et al. [14] have raised the issue of "creeping determinism" in ISS science operations, particularly with respect to reduction in crew autonomy and it's affect on the research being conducted on that platform. Although there was no effort to evaluate this issue on RATS 2010, an understanding of the benefit of different levels of autonomy should be undertaken. Further, it will be critical to differentiate between creative science interaction between the crew on a planet's surface and a ground science team, and more restrictive "over the shoulder" supervision of in-space crew by ground controllers.
- If the evaluation of continuous communications on science operations is a critical test objective, the communications infrastructure should ensure that high-fidelity, stable communications exists at all science stations.
- Team members need to stay in a particular job greater than 3 day at a time.
- Team members need sufficient pre-mission training and practice exercises to ensure that a team member's experience in the tests is a reflection of what is working well and what is not, rather than being a reflection of inadequate training. This is also critical for the crewmembers conducting the field geologic investigations on the ground.
- Improved technology is needed to make it easier and faster to assimilate data sets. For instance, it is simple to speed read transcripts, but impossible to "speed listen" to a sound file at high playback rates.
- The data set that the SSOT needs to assimilate within a given shift should be better defined in order to increase operational efficiency.
- Data mining needs to be facilitated with consistent, clear file structures and graphical user interfaces so reviewing a particular data set does not lead to a lengthy "treasure hunt".
- Better capability for manipulation of datasets, including GIS-based interfaces, is needed to extract to critical data from large mission data sets for SSOT operations.
- The crew needs to be able to review imaging data sets in real time to correct any imaging deficiencies prior to leaving a particular locality, and this needs to be part of the nominal list of tasks completed by the crew during science operations. This applies to all communications conditions, but it is clearly a requirement for reduced communications where a Science Support Team cannot review the quality of a down linked image and correct deficiencies in real time. Improving the capability of the crew to manage the quality of the data they are collecting will improve mission science return and crew autonomy, and allow science operations teams to be more engaged in scientific discovery rather than data collection oversight and crew time management.

The planning for Desert RATS 2011 has been underway during the preparation of this manuscript, and the lessons learned in 2010 are already being applied to the next test in the series.

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