The Effect of Different Operations Modes on Science Capabilities During the 2010 Desert-RATS Test: Insights from the Geologist Crewmembers

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Acronyms

2/Day: Twice-per-day Communications

CC: Continuous Communications

CFN: Crew Field Note

D&C: Divide and Conquer

Desert RATS: Desert Research And Technology Studies

EVA: Extra Vehicular Activity

IVA: Internal Vehicular Activity

L&F: Lead and Follow

MCC: Mission Control Center

SEV: Space Exploration Vehicle

Abstract

The 2010 Desert RATS field test utilized two Space Exploration Vehicles (prototype planetary rovers) and four crewmembers (2 per rover) to conduct a geologic traverse across northern Arizona while testing continuous and twice-per-day communications paired with operation modes of separating and exploring individually (Divide & Conquer) and exploring together (Lead & Follow), respectively. This report provides qualitative conclusions from the geologist crewmembers involved in this test as to how these modes of communications and operations affected our ability to conduct field geology. Each mode of communication and operation provided beneficial capabilities that might be further explored for future Human Spaceflight Missions to other solar system objects. We find that more frequent interactions between crews and an Apollo-style Science Team on the Earth best enables scientific progress during human exploration. However, during multiple vehicle missions, this communication with an Earth-based team of scientists, who represent "more minds on the problem", should not come at the exclusion of (or significantly decrease) communication between the crewmembers in different vehicles who have the "eyes on the ground". Inter-crew communications improved when discussions with a backroom were infrequent. Both aspects are critical and cannot be mutually exclusive. Increased vehicle separation distances best enable encounters with multiple geologic units. However, seemingly redundant visits by multiple vehicles to the same feature can be utilized to provide improved process-related observations about the development and modification of the local terrain. We consider the value of data management, transfer, and accessibility to be the most important lesson learned. Crews and backrooms should have access to all data and related interpretations within the mission in as close to real-time conditions as possible. This ensures

that while on another planetary surface, crewmembers are as educated as possible with respect to the observations and data they will need to collect at any moment.

1. Introduction

Desert Research And Technology Studies (Desert RATS) is a multi-year series of tests of NASA hardware and operations deployed in the high desert of Arizona. Conducted annually since 1997, these activities exercise planetary surface hardware and operations in relatively harsh conditions where long-distance, multi-day roving traverses are achievable. Such activities not only test vehicle subsystems, they also stress communications and operations systems and enable testing of science operations approaches that advance human and robotic surface exploration capabilities as well as the ability to conduct scientific studies, including field geology.

Desert RATS 2010 tested two crewed, electrically-powered rovers that were designed as first-generation prototypes of small pressurized vehicles. Each rover, or Space Exploration Vehicle (SEV) [1], provided the internal volume necessary for crewmembers to live and work for periods of at least 14 days, as was demonstrated during the 2009 field test [2]. The SEVs also enable the crew to conduct extra vehicular activities (EVAs) through the use of rear-mounted suit ports [2, 3]. The 2010 test was designed to simulate geologic science traverses over a 14-day period through a volcanic field that is analogous to volcanic terrains observed throughout the Solar System.

The test was conducted between 31 August and 13 September 2010 and is described in detail by Kosmo et al. in this issue [4]. Two crewmembers lived in and operated each rover for a week with a "shift change" on day 7, resulting in a total of eight test subjects for the two-week period. Each crew consisted of an engineer/commander and a field-experienced geologist. Three of the crew commanders were experienced astronauts with at least one Space Shuttle flight. The field geologists were drawn from the scientific community, including NASA centers and academia, based on funded and published field expertise. As such, each rover crew was capable of providing feedback regarding the effect that different operational modes had on mission operations and science capabilities as compared to actual spaceflight missions and terrestrial field geology research.

Here we present the opinions of Desert RATS geologist crewmembers on the effect that different operational modes had on our overall science productivity during the 2010 traverses. Unlike other papers presented in this Issue [1, 5,] our results are not quantified or based on metric analyses Instead, "science productivity" as discussed here is a qualitative assessment made by the authors from their perspective on working inside the SEV and while on EVA as compared to our regular field geology projects that support our career research. We note here that the authors reached a consensus regarding the points raised in this report. The goal of this report is to explain the way in which the crewmembers functioned based on varying the mode of communication and operation, and how each approach might be best utilized in similarly-designed future spaceflight missions. Differences in the approach to handling the operations and communications modes among the crews are discussed. Spaceflight constraints will always hinder planetary fieldwork when compared to traditional terrestrial field science, but our work strives to ensure that future spaceflight crewmembers are prepared to maximize their scientific efficiency within those constrained working conditions.

2. Methods

The 2010 test explored different communications and operations modes that we briefly describe here. For a more detailed description of the modes tested during Desert RATS 2010 see Kosmos et al., and Eppler et. al., (both in this issue) [4, 6]. Three days of each week were tested with the rovers in continuous communications (CC) with mission operations and the science support teams. Another three days were tested with communications for only ~1 hour in the morning and ~1 hour at the end of the traverse, called twice-a-day communications (2/Day). During 2/Day, the SEVs were to remain generally within line-of-sight and in communication with each other. Constrained by these requirements, the separation distance was < 500 m.

Using two SEVs also enabled the testing of two different operations modes (Figure 1). We tested an exploration strategy in which the two SEVs executed unique traverses, called divide-and-conquer (D&C). The second mode of operation had the rovers follow one another on the same traverse, called lead-and-follow (L&F). Each mode of operation was combined with a communication mode for the field test as discussed in the following section. Matrices were designed to measure the data quality and exploration productivity of each mode, generally finding that both improved during CC and D&C [1]. To complement those quantitative analyses, here we report the opinions of the geologist crewmembers as to which aspects of each mode were considered advantages and disadvantages in conducting science operations.

INSERT FIGURE 1 HERE

Within this report we use several terms for which we provide our intended meaning here. The Science Team and Science Backroom require distinction. The Science Team is everyone involved in the science of the Mission. This includes the scientists involved in the pre-Mission science planning, as well as those who filled Science Backroom roles during the test and field scientists who observed the work of the crew during the test. The Science Backroom is a subgroup of the Science Team that is devoted to handling science operations for an SEV during a traverse. Each Science Backroom was led by a Science PI and included personnel dedicated to various aspects of the work that was underway by crewmembers. Most Science Team members cycled through different positions within a Science Backroom, as well as into field observations roles throughout the test. As such, the Mission and traverse planners were sometimes located within a Science Backroom, but were not always present in one or both backrooms. Each SEV had one dedicated Science Backroom during CC.

We use the terms EVA, Station, drive, and traverse. An EVA is any situation in which one or both crew members have egressed, or exited, from the SEV through the suitport and are conducting science or rover maintenance tasks. A Station is a location, generally predetermined by the Science Team or the Mission Control Center (MCC), at which the SEV has stopped to conduct scientific observations or maintenance. A Station might or might not include an EVA. A drive involves a SEV moving between Stations. A traverse is a series of stations and drives. For example, a daily traverse might contain three Stations, while a crew's complete seven-day traverse includes all Stations visited during their portion of the Mission. We also discuss prebriefings and debriefings, including those among the crews and those between crews and with the Science Backroom or MCC. A prebriefing is a meeting between relevant parties prior to an action, such as an EVA or the day's overall activities. A debriefing is a similar meeting held after the activity is complete. When discussing both types of meetings in a general way we use the word "briefings". Prebriefings and debriefings, and their purposes, are discussed in additional detail by Love and Bleacher [7] in this issue.

3. Crew Daily Science Activities

The 2010 Desert RATS field campaign operated under two operations/communications mode combinations: D&C with CC; and L&F with 2/Day. The Mission was designed to assess each operation and communication mode independently, and no Mission-level goals included the assessment of paired modes. As such, we did not operate under each possible combination of operations and communications modes. The actual combinations were, in part, chosen for safety reasons because when not in communication with the MCC and Science Backroom the SEVs needed to be in close proximity for hazard and emergency mitigation, which essentially eliminated the possible combination of D&C and 2/Day. CC and L&F were not paired at any time during the 2010 field test. Although these test modes were assessed independently, we present our observations and conclusions in the paired format in which the field test was conducted.

Within these modes of operation the science team and crew worked together to develop geologic hypotheses that could be tested with field observations that were enabled by the mobility of the SEV and EVA capabilities of the crew [8, 9]. The ultimate goal of the 2010 Desert RATS field campaign was to identify ways to best preserve idealized – and, perhaps, "traditional" – terrestrial field capabilities within a constrained human spaceflight environment. In this section we describe the daily science activities within each combination of communications and operations modes. Each combination resulted in distinctive test outcomes, each of which would have unique relevance to different styles of missions and approaches to scientific data collection. For instance, missions to Mars or asteroids are unlikely to experience

CC, therefore preparation for dealing with delayed or limited communications is critical regardless of the operations mode that might selected.

3.1 Continuous Communications and Divide-and-Conquer

Activities performed by an individual SEV crew and their Science Backroom during CC essentially adopted a strategy similar to that used by the 2009 crews and Science Backrooms [2, 10]. During this portion of the test, the operations mode enabled the SEVs to spread out and cover more ground (Figure 1). This capability supported the exploration and collection of samples from a more diverse set of geologic units. Furthermore, CC enabled us to continuously work with a host of scientists in the backroom to develop, in real-time, hypotheses that might be testable within an ongoing EVA, traverse, or during the course of the entire mission [6]. The Science Backroom worked continuously with MCC to maintain a balance between science objectives and changes to the daily timeline, in part, necessitated by delays during drives or EVAs and other operational constraints. Regular updates were provided to the crew regarding their timeline by the Science Backroom and MCC so that neither crewmember within an SEV was required to focus significant attention to changes in the timeline. Therefore the geologist crewmember, in particular, was free to focus on geologic descriptions during drives. The backroom was also able to provide support to the crew by indicating when the image data or sample description information was not adequate (e.g. poor sample placement within the image frame, the lack of specific information from a sample description, etc.), thereby enabling the crew to take corrective measures. This was particularly critical during EVAs in the 2010 test because the crews were unable to see the image and video data that they were collecting [11].

Prior to the beginning of an EVA, each rover's crew would hold a short prebriefing amongst themselves to lay out a specific exploration and sample collection strategy for that site. During CC, the science support team was able to weigh in on this briefing, but, in general, gave the crew the final decision-making authority for specific Station parking spot selection and EVA plan development. This represents a lesson learned from the 2009 field test during which pre-acquired robotic rover data sometimes led to tension between the Science Backroom and crew. On occasion during the 2009 test, the Backroom questioned the real-time site selection and sample location decisions of the crew because of occasional discrepancies between the robotic reconnaissance data and what the crew was seeing real-time. During the 2010 field test, the Science Backroom had access to prior data collected from other sites, the geologic map, and, based on images acquired from a camera mounted on the SEV's mast, a wider field of view than the crew. The Science Backroom could use these data as references to help direct an EVA, whereas the crew could not access any of those data in real-time while on EVA. CC also enabled the backroom to operate the SEV-mounted cameras during EVAs to document the surrounding terrain or keep track of the crew's activities, including the collection of geologic observations and samples [12].

Although we found communications with the Science Backroom to be beneficial, we did identify some drawbacks. To reduce the overlap in communications between two SEVs and their respective Science Backrooms, the Desert RATS team placed each SEV on a separate communications loop. Although the SEVs had a voice loop for communications between one another during drives or IVA (Internal Vehicular Activity) operations, it was not the default configuration. In practice, we found that communications between SEVs during the CC traverses were limited because it was logistically difficult to enable the communications link. Furthermore, in order to initiate communication with the other SEV during IVA, the crews were required to ask permission from the MCC. For this reason, the geologist crewmembers never communicated between rovers during the week 1 CC days. During week 2, the geologist crewmembers did communicate during CC, but only rarely and informally. In addition, it was not possible, in either of the communications modes, for an IVA crew of one SEV to initiate communication with the other crew while the other crew was on EVA. Because EVA schedules often did not overlap, or changes in the timeline caused planned overlaps to become out of sync, significant periods of time were therefore essentially inter-SEV communication blackouts. As such, we describe inter-SEV communications during CC as difficult. We made up for this on-the-ground communications deficiency by holding unscheduled 30-60 minute SEV-to-SEV debriefs daily during crew personal time, typically at the end of the day. However, this approach negates the potential benefit of each crewmember's complete awareness of the other's observations and hypotheses in real-time, which would have been scientifically and operationally advantageous during daily activities, and completely eliminated the Science Backroom from the discussion.

3.2 Twice-a-Day Communications and Lead and Follow

The 2/Day and L&F scenarios were new test variables for the DRATS field tests. During 2/Day and L&F operations, the crew took on a significantly increased responsibility for timeline management. At the end of the morning prebriefings, the crews were told at what time that evening they were expected to reestablish communications with the MCC. Once the SEVs ended communication with the MCC, the crews were responsible for ensuring that the science objectives were met within the time available for that day's traverse. The first step towards doing so was effective timeline management, which added to the crew workload as they did not have

MCC to manage this activity. Each SEV crew conducted timeline management independently as a means of redundancy, thereby enabling cross-checking between SEV crews for this important activity. If time was lost along the day's traverse, the crews were responsible for determining in real-time how best to preserve the rest of the day's science objectives within the shortened timeline. This task included decisions in which lower priority science objectives were dropped to ensure that higher priority objectives could be met. To help minimize the added responsibility on the crews during 2/Day, the morning Science Team prebriefs evolved throughout the 2010 field test to include a detailed prioritized list of Station objectives. This helped decrease crew time spent adjusting the daily science plan to the evolving timeline. During the second week of the test, the Science Team prebriefs continued to evolve to include a "big picture" science overview that linked the day's objectives to the observations and lessons learned throughout the previously completed traverse days. This development provided the crews with some context to better judge the importance of previously prioritized tasks, and this improved our real-time decision making capabilities.

Because 2/Day communications limited the interactions between the SEV crews and the Science Team and MCC, the daily activities of the crews were not closely monitored [6]. Furthermore, because the week 1 crews did not provide an operational debrief to the week 2 crews, neither week's crewmembers had a preconception as to how to conduct their 2/Day and L&F operations within the Flight Rule constraints [6]. As such, during 2/Day and L&F operations each week's crews developed a unique approach to conducting a traverse under these conditions. Those differences, as well as their unique strengths, are outlined in the following paragraphs. As is the theme throughout this report, we show that each approach holds advantages that should be preserved in future operations tests and Space Flight Missions.

In general, L&F operations kept the SEVs within line-of-sight and rarely exceeded 500 m of separation. Although the phrase Lead and Follow suggests that the SEVs would operate in close proximity at all times, the stations that were planned for each crew by the Science Team were often several hundred meters apart. As such, the crews for each pair of SEVs developed their own strategy for working together both during drives and at Stations. The primary differences between the week 1 and week 2 strategies were associated with real-time Station selection and drives between them. Week 1 crews conducted all of their drives in a closely spaced formation, but separated to farther extents during Station selection without necessarily attempting to reach the specified site that was planned by the Science Team. Week 2 crews conducted their drives in a less strict spatial formation but attempted to reach the Station sites that were planned for them. During CC the crews received continual input from the Science Backroom regarding Station selection and drive locations, but during 2/Day and L&F the crews depended on each other to make those decisions. Despite these differences within L&F, both crews operated within the constraints that were designed for the field test during L&F operations. These differences highlight the importance of field tests as these unique styles enable unique capabilities that are not necessarily easily planned from an office.

During week 1, the SEVs remained relatively close to one another during L&F drives generally a few 10s of meters apart (Figure 1). Upon nearing a Station, the SEV crews would discuss the best sampling and site selection strategy. Because week 1 crews always drove in close formation this usually involved reaching a point between the Stations that were planned by the Science Team (often 200-300 m separation). The SEVs would then split off towards their respective Stations while conducting regular radio checks to ensure that communications were maintained. At a given Station, the crew with the highest priority objective usually chose a parking location first that enabled them to address that goal, and the crew with lower priority objectives would select a parking spot that maintained communication with the other SEV but provided the opportunity to conduct the most effective field work. If the geologist crewmembers believed that they would likely sample the same material, and either crew could identify an alternative Station nearby that would enable sampling of an unexplored unit that was unrecognized by prior analysis of remote sensing data, then the lower priority tasks were dropped and a real-time decision was made to explore the new unit (see Hurtado et al. [12] this issue for more details on geologic fieldwork strategies during EVAs). Prior to the first crew's start of an EVA, both SEV crews would determine at what time their ingress into the SEV at the end of their EVA should begin such that both SEVs could meet at an agreed upon rendezvous point at the same time to begin the next drive in close formation. In other words, crew agreement upon the time for ingress initiation was a critical decision point during week 1. If the geologists determined that a site that was different from the one selected by the Science Team was to be explored, then their crew was responsible for ensuring that their ingress after EVA began at the time necessary to accommodate the SEV rendezvous. This approach always kept the SEVs within a few 10s of meters during a drive, which had some advantages as described below. We refer to this L&F tactic as "Paired Exploration".

During week 2 the crews generally adopted a strategy in which the SEVs attempted to park at or near the predetermined Station locations (in as much as was safely and logistically possible, similar to selecting a parking spot during D&C). The week 2 crews also held prebriefings to determine EVA durations and ingress times, but were less regimented in identifying a post-EVA rendezvous point and time. Because neither SEV was expected to wait for the other at a rendezvous point before the drive to the next station, this approach enabled the SEVs to travel at a separation distance of up to ~100 meters opposed to ~10-40 meters as was typical of the Paired Exploration strategy utilized in week 1. As such, week 2 crews took less authority to choose a specific parking location unique from the traverse plan, but did spread out during drives enabling unique observations from each crew. We tentatively refer to week 2 crews L&F tactic as “Recon Exploration”, and it had unique advantages as described below.

Regardless of the Exploration style they used, Paired or Recon, the crews were always in close enough proximity to provide situational awareness feedback to each other. This was advantageous when crossing rough terrain, such as gullies, during which the SEV in front could find the safest path and relay that information to the trailing SEV. Similarly, the trailing SEV could reach higher ground and provide descriptions of the path ahead to the lead SEV to help them select a path. This was done nearly continuously as the geologist crew members discussed the geology and the crew commanders discussed how to traverse across it.

The crews worked together during IVA operations on the L&F traverses to acquire data that was complementary and did not repeat observations at a station. During CC and D&C operations, a SEV crew would sometimes collect Crew Field Notes (CFNs) [11, 12], typically consisting of a single image from a camera mounted on the SEV’s mast and a recorded voice note. Since the SEVs were at different Stations during D&C, each crew’s CFNs and Panoramic images were unique, and crews had to spend time acquiring both sets of data, or only acquire one data type. During 2/Day and L&F Paired Exploration operations, the SEV crews worked in concert such that one SEV crew would collect a CFN at a stop while the other SEV further documented the area with a GigaPan (self stitching panorama from a second camera mounted on the SEV mast) [13] that was simultaneously acquired and included the SEV that was collecting a CFN image of a smaller scale feature. This style of complementary IVA data collection provided improved geologic context for CFN data, as opposed to a single CFN or GigaPan image acquired by a solitary SEV. This adaptation was a logical step as the collection of a CFN by one SEV essentially forced the other SEV to stop and wait during Paired Exploration, and this potentially wasted idle time was put to good use.

During Recon Exploration, the SEV crews did not wait for each other, either at a rendezvous point or during CFN image acquisition. As such, potentially wasted waiting time was minimized or eliminated entirely. In situations when one crew completed their EVA earlier than their partners, the first crew pressed forward on the traverse. Although this style of exploration never resulted in significant separation, and the crews were not operating independently of one another, this enabled the lead crew to scout out or recon the best path for the following SEV's drive or sites for image acquisition. As such, the first SEV crew was able to provide advice on pathway and parking spot selection. However, in cases when the SEVs during week 2 were separated by greater distances than during week 1, the local, precise situational awareness enabled by Paired Exploration was reduced when crossing difficult terrain. Greater separation distances also prohibited the Recon Exploration crews from acquiring complementary CFN and GigaPan data. However, it is not clear how advantageous these data were/are to the Science Team. Perhaps not all CFNs would experience an increase in value when complemented with a GigaPan. This represents a possible trade study for future tests in which L&F operations are considered. These differences only recently came to light, due to the preparation of this report, and, as such, are still being considered by the Science Team. This point demonstrates the importance of preparing reports such as those in this Special Issue to help draw out possibly overlooked real-time test adaptations and outcomes.

As mentioned above, L&F operations, regardless of Paired or Recon Exploration approaches, often led to repetitive sampling of the same geologic units as the traverse Stations regularly restricted the crew to the same area. This could be viewed, albeit problematically, as a disadvantage in that we covered less ground and explored fewer units [12]. Conversely we found that while working with the other SEV we were able to conduct more detailed process-related observations. An example involved a gully that had eroded into the base of a cone (Figure 2).

[INSERT FIGURE 2 HERE]

During EVA both crews crossed the gully at ~ 300 m separation and were able to determine the amount of incision and gully widening over that distance. A stop at the same location during D&C would have collected one set of the same samples and observations, but may have provided little input on the erosion process other than that it had occurred.

During 2/Day we communicated nearly continuously between SEVs. Although CC interaction with a backroom enabled more experienced minds to work on a science problem, having two sets of trained eyes on the same terrain also proved advantageous. During both Paired and Recon Exploration, the crew geologists were able to discuss their observations and hypotheses throughout the traverse. This enabled the crew to quickly compare results, both prior to and after EVAs, enabling improved Station selection and EVA planning. This sort of real-time traverse refinement informed by first-hand analysis in the field is not possible with a remote science team and was a benefit to executing efficient and scientifically effective EVAs. Similarly, the two geologists could, when practical on L&F days, convene on the outcrop during EVAs in order to compare samples and observations. This was an effective way of synthesizing geologic understanding while still in a position to make additional observations. Having communicated throughout the day's traverse reduced the amount of time spent discussing work during crew personal time at the end of the day. However, during 2/Day we found that the scheduled ~60 min science debriefs at the end of the day were not adequate to convey our daily observations and hypotheses to the science team. This could essentially represent a loss of data between crew and backroom at some points, particularly if there are bottlenecks or points-of-failure in the automated transfer of digital files between the SEV and Science Team. This highlights the need for effective data flow between all parties. Regardless of operation or communication mode, we collected annotated GigaPan images, maintained spreadsheets, and documented the traverse with text documents from inside the SEV [12]. However, it was not always clear to us which of these files were transferred, received, and analyzed by the Science Team prior to each morning's prebrief.

4. Findings and Recommendations

The 2010 Desert RATS field test essentially represents a set of "end-member" communication and operational modes that could be used during dual rover planetary exploration. In the preceding section we discussed differences in the daily science operations within the SEVs during the traverse. Both operations and communications modalities pose advantages and disadvantages to the geologist crewmembers and their ability to collect scientific data. Based on the geologist crewmembers' experiences managing these challenges, we present recommendations for how to maximize the science capabilities of future surface exploration missions that might utilize some variants of these end-member cases. We note that despite the limitations of a given operations or communications mode, the crew, Science Team, and MCC adapted quickly to best exploit the advantages present within the operations test. We believe this to be consistent with all human spaceflight endeavors, and it highlights the necessity of realistic analog tests and training prior to Mission activities. No lesson learned during an analog test is insignificant. Any experience-based method for streamlining the adaptation pathway towards maximizing the value of science or mission operations activities within a given set of limitations is highly valuable, even if it is not realized for years or even decades.

It is important to recognize that the crew is but one portion of the Science Team. The ultimate science goal of any mission is to provide the most thorough scientific understanding possible of an area of exploration. In the case of Apollo, much of this overall understanding was not achieved for years to decades afterwards [14], and continues to this day. As such, the goal is not necessarily that the crew themselves gain that understanding in real-time, but that they work with the Science Team to collect the most important data to enable both real-time and continued science in the years to follow. After all, the hypothesis development that drives scientific advances does not end with the mission. However, to ensure that the correct data are acquired, the crew must be involved in hypothesis development and have as clear an understanding of the overall science as everyone else on the Science Team.

With this in mind, the geology crewmembers generally agree that a better overall scientific understanding of the 2010 test region was ultimately gained during CC and D&C. When the Science Team was given time to ingest and compare results from both rovers over a larger area of exploration, a more complete scientific story resulted. However, we also felt that we had a better personal recognition of the larger science story in real-time when we communicated with our partner SEV's crew regularly during 2/Day activities. This point is discussed by Litaker and Howard (this issue) [5] based on metric data analysis of the crew's experience. They state:

“Interestingly, during debrief sessions; (sic) the crew reported in 2/Day they had a better understanding of the bigger scientific picture than in CC due to the communications between the science members of the crew.” Consistent with our discussion above, we clarify this point here by stating that, with respect to communications, we found value in real-time access to the knowledge gained by the other crew geologist. However, while this led to an improved personal understanding of the regional science, ultimately the overall science understanding gained during the mission was best maximized during CC with additional scientists in the backroom. Furthermore, potential loss of data during 2/Day was a genuine risk as the crew were not able to update the Science Backroom about their thoughts and observations in real-time. As such, data could be truly lost in this communications mode. This point highlights the importance of ensuring that the crew are kept, as best as possible, in the loop regarding hypothesis and science story development including data from both SEVs during the daily pre- and debriefs. We also reiterate that the Science Team was aware of this issue throughout the 2010 test as evidenced by the continually improving briefing strategies outlined in Section 3.2. This point also clearly demonstrates that both end-member communications modes hold some value that might be usefully incorporated into future Space Flight Missions. We discuss this point further in the following paragraphs.

We note here that, although the test included a CC scenario, at no point did we truly experience continuous communications with MCC or the Science Backroom due to difficulties in deploying test assets to maintain communications in a terrain with significant relief. We found it easier to operate when planning for intermittent communications than to expect CC but, in reality, experience intermittent communications. As a result, we recommend that a series of fallback communications protocols should be established to deal with loss of signal situations, particularly because continuous communication is not likely to exist for a mission to most planetary surfaces. During CC in week 2, the SEVs crew did begin creating a form of fallback plan by discussing the goals of the upcoming EVA during each EVA debrief. This turned out to be useful in one instance where the crew lost communications with their Science Backroom prior to arriving at a Station, the exact time when the prebrief would typically have been underway.

Based on the communications tests we feel that the best overall science was achieved when more brains were working on the science problems. Ideally we prefer regular communications with a Science Backroom to help develop competing hypotheses and tests to differentiate between them. When not in regular communications with a Science Backroom, the crew relied heavily upon inter-SEV discussions to increase the value of our science results as compared to working in complete isolation. However, even if near-continuous communications with the Science Backroom are achievable, we still recommend that the crews should be provided time in the schedule to communicate among each other during a traverse. Perhaps this will require developments in communications infrastructure to enable multiple loops that allow simultaneous communications without interference. Lacking such a development, the MCC and Science Team must understand that this type of inter-crew communication is mission critical, and not an action to be occasionally accommodated. As mentioned earlier, having multiple personnel working in the Science Backroom is beneficial, but so is having a second set of eyes on the ground and a resultant increased contextual understanding of the area of exploration. Neither completely replaces the value of the other and the advantages of both should be preserved even when operating in near-continuous communications with a Science Team.

To ensure flow of information between rovers (and their Science Backrooms) the concept of a single Mission Science Principal Investigator (PI), with oversight of both SEV teams (crews and

Science Backrooms), should be explored. During the 2010 test, the Science Backrooms were located in adjacent rooms, but science communications between them were informal and sporadic [6]. During CC, our communications between SEV crews were also minimized so as not to interfere with EVAs or ongoing discussions between the other crew and their Science Backroom. The Mission Science PI would be responsible for developing the overall science story for the mission so that neither SEV team is working in isolation as a consequence of trying to reduce the impact of too many voices speaking simultaneously on communications loops.

During this test, the data collected while on EVA [12], including imagery, video, and voice, were generally not available to the crews for review. Young et al. (this issue) [11] recommends that, at the very least, crew members should be able to monitor their camera status in real-time, which is a capability that has already been added for the 2011 Desert RATS field test. Here we additionally recommend that all data should be available between SEV crews, and ultimately between EVA crewmembers in real-time. Regardless of data display and sharing capabilities, the Mission Science PI would ensure that all crew and Science Backroom participants are aware of relevant observations from their counterparts throughout the traverse, and that neither team is working in isolation.

In addition to a Mission Science PI, we recommend that a geology-trained crewmember should be identified as a Field Science PI in much the same way that an overall Crew Commander is identified between the SEVs. The Field Science PI should have final decision-making authority on the ground. The Field Science PI would be most important when communications are limited to several times per day opposed to CC. Although we did not encounter a problem in this aspect of the test during 2/Day, it is obvious that somebody should have overall science decision-making authority on the ground, particularly when the crew are responsible for maintaining their own timeline and when Stations and EVA plans might need to be modified or dropped entirely.

We feel that the daily science debriefs during 2/Day did not enable us to adequately convey our scientific lessons learned from the day's traverse, thereby limiting the overall science learned during the mission. This point highlights the importance of science debriefs during limited communications situations between the crew and Science Backroom. The format of this discussion was not well developed prior to the field test and evolved as the test progressed, but we suggest that it should be significantly structured so that the crew can easily, succinctly, and completely convey the important aspects of their day's traverse. Additionally, the point of contact that represents the Science Backroom to the crew should remain consistent and have a strong working knowledge of the day's activities and results. One possibility would be that the science debrief is led by the Field Science PI. That individual would synthesize and summarize both SEV's results prior to the meeting and then present this to the Mission Science PI during the briefing itself, as opposed to each geologist crewmember discussing their own, possibly redundant, observations. Furthermore, if real-time interactions are possible during briefings it would be beneficial if the crew and Science Team could interactively view and annotate the same data.

In order to maximize the efficiency of the daily prebriefs and debriefs, the data flow framework must be clearly understood between the SEVs and their Science Backrooms. This was particularly important during 2/D. The crew often created what was essentially a science abstract for the day's traverse, including new hypotheses and answers to questions that had been raised by the science team in the morning prebrief. However, sometimes this information was not received by the backroom due to uncertainty as to where digital data was to be stored in the SEV computer system for upload/download and a lack of a mechanism for explicitly indicating if and when those data were transferred. In these instances, confusion arose between the crew and their Science Backrooms because it was not clear which data had been transferred and particularly which data had been included in briefing discussions. As such, we recommend that science prebriefings should always indicate what data were used in the development of that presentation. Furthermore, a standard set of daily data products should be expected and documentation should be kept to indicate where those data should reside and when those data have or have not been transferred. To address these issues, a dedicated data manager position with data transfer oversight should exist on the Science Team. We also reiterate here the point that data should also be easily transferrable between the SEVs and that the crews should have access to all the data that they have collected throughout their traverse, something that was not possible during Desert RATS 2010.

Early in the test, the morning science briefings focused heavily on sample collection objectives. As the test progressed, the morning science briefings began providing us with the geologic hypotheses that drove the sample requirements. Inclusion of the crew in the hypothesis development and data collection planning process is critical for maintaining the crew's focus on science goals. Although the Science PI (a position that existed within each Science Backroom during the 2010 test, such that each SEV had a Science PI) was located with the Science Team, the crews were the eyes on the ground. Providing the crews with the current hypotheses and tests (samples, observations, and other data) to differentiate between them ensures that the goals of the Science PI will be met. This is an interaction between the crews and their Science Backrooms that did improve throughout the traverse regardless of operating or communication mode. However, during CC the backroom was capable of updating the crew in real-time about hypothesis development, whereas during 2/Day the crew were solely responsible for real-time hypothesis development and testing, and as such the Science Team were updated twice-per-day. As such, the importance of the daily science prebrief increases dramatically when communication opportunities decrease within a given mission day, and the structure of the prebrief might be fundamentally different depending on the frequency of communications during the day and the length of time available during the meeting.

Regardless of the operations mode for a mission, traverse design is a critical component as the traverse is essentially the scientific backbone upon which the mission is built. As such, traverse design should be led by a PI who will be in the Science Backroom during its execution, potentially occupying the role of Mission Science PI as discussed above. It is critical that this person have an intimate understanding of the traverse for real-time decision making for both rovers based on the collection of new data. Furthermore, it is critical that the crew and the daily brief/debrief leads also possess an intimate understanding of the daily traverse plans, which is most easily established through involvement in traverse plan development.

5. Conclusions

Many Solar System targets have been identified for possible human exploration missions in the future, and these choices are based on numerous scientific rationales. Regardless of the destinations that are chosen, the humans who explore these locations will be faced with many operational constraints on their ability to conduct scientific analyses. Although science will be a significant driver of future human exploration, safety concerns and physical limitations will largely control the frequency and duration of delays in communications between crews and supporting scientists back on Earth. This will also determine the allowable separation distances between assets and the mode of operation among multiple spacecraft assets, both robotic and crewed. As such, we do not suggest that any of the modes of operation tested during Desert RATS 2010 is an obvious better option, as it is not clear what the cost of those capabilities might be that could offset their potential advantage. All modes that were tested in the 2010 Desert RATS field campaign revealed limitations in our capabilities as field geologists when compared to the standard terrestrial fieldwork with which we are most accustomed. However, each mode of operation that was tested did provide unique advantages. Our goal is to highlight those advantages so that when technological constraints are placed on future human explorers, they are mitigated using an approach that maximizes scientific efficiency within that architecture.

We find that regular communications between the crews and their supporting scientists enables the most effective real-time hypothesis development and testing throughout a traverse. However, the communication infrastructure established for the 2010 test did not enable adequate communication between crews, an equally critical capability to have. When communications with the Science Backroom were infrequent, the crews relied heavily upon each other for real-time hypothesis development. As such, both communications modes that were tested in 2010 lead us to conclude that communications with a backroom on a regular basis are important, but that discussions between geology-trained crewmembers should not be lost in order to achieve this capability. Having more minds working on the problem is important, but so are discussions between those who have the eyes on the ground. Both are important and should not be mutually exclusive. In fact, we argue that they are likely mutually advantageous.

Different separation distance between crews and rovers can enable unique and beneficial capabilities. Larger separation distances between rovers during a dual (or more) vehicle mission enables the crews to spread out and cover more ground. This capability provides opportunities for crews to encounter, explore, and sample a more diverse set of geologic units, thereby exposing the science team to a broader, more regional understanding of the exploration target. Although a decreased separation distance might reduce the likelihood of the mission encountering different geologic units, closer proximity observations at times during the 2010 test provided higher detail process-related understandings of the local geology.

Regardless of the mode of operations and communications, the need for competent data management, transfer, and accessibility in real-time is consistently a lesson learned. Multiple-rover missions require data sharing capabilities between the crews, encompassing quantified measurements, sample information, observations, and hypothesis development. In situations where multiple vehicles will each have a dedicated Science Backroom it is critical that one person on the mission's Science Team be responsible for integrating each rover's data and interpretations into the overall science story. Furthermore, that story must always be shared with the crews who might not have had a chance to fully recognize the value of the other crew's observations during a traverse. An observation or sample from one rover might be the critical piece of information that drives an important realization by the other rover.

Analog tests, such as the Desert RATS 2010 field campaign, represent the opportunity to collect critical operational data related to potential future solar system exploration missions. Although no analog test can fully capture the specific and complex set of architectural constraints that will eventually face the humans who explore other planets, satellites, or asteroids, we can begin to outline the methods in which we might best work within those likely constraints. Even more important is the identification of unrecognized difficulties so that we might begin incorporating them into future analog tests. In this context, we conclude that the

2010 test was a success, but is just one step in a series of many that are needed in the future to best enable human exploration of our solar system.

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Figure Captions

Figure 1. The top image shows a portion of the San Francisco Volcanic Field, including S P Crater and Colton Crater (data product credited to Google). This region was the site for the 2010 Desert RATS field test. The dashed line denotes the extent of the images at the bottom left and right. The panels labeled D&C and L&F show the same areas. The colored lines show the traverse paths followed by SEV A (red line) and SEV B (blue line) during different operations modes. The lines are based on the GPS navigational data collected by the SEVs during their traverses. D&C data were collected on 9/1/2010 by the week 1 crews and L&F data were collected on 9/12/2010 by the week 2 crews.

Figure 2. Images A and B are example still images that were acquired as CFNs (Crew Field Notes) using the crewmembers' backpack cameras during 2/Day EVAs [12] within L&F operations. These images were obtained at the locations marked A and B on the map at the bottom of the figure. The orange and red lines show the rover paths for SEV A and SEV B, respectively. The green and blue lines show the EVA paths for the geologist crewmembers from SEV A and SEV B, respectively. The dashed black line shows the trend of a small gully that has formed at the base of a cinder cone. Although the primary science objectives at this location were to collect samples of the cone and the loosely consolidated surface materials around it, analysis of the CFN data shows that the gully dimensions vary from ~ 2 m wide and 10-30 cm deep at point B to ~ 3 m wide and 1 m deep at point A. This type of process-related, observational data contributes to the science value of a Station [13]. However, we note the potential difficulties in estimating scale from context images of the local geology (A). Unlike

traditional field work, it is not always easy to deploy a physical item for scale at some distance from the site at which the crew acquire images of the local geology. These data were acquired on 9/4/2010.

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Jacob Bleacher is a research scientist at NASA's Goddard Space Flight Center in the Planetary Geodynamics Lab, Solar System Exploration Division. Jake's research focuses on the development and modification of planetary volcanic terrains through a combination of terrestrial field studies and spacecraft data analysis. He combines his expertise in field and planetary geology to help build and test the science capabilities of NASA's newest instrument, suit and rover technologies and has served as Desert RATS crew since 2009. He holds a B.A. in Geosciences from Franklin & Marshall College and a Ph.D. in Geological Sciences from Arizona State University.

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Figures

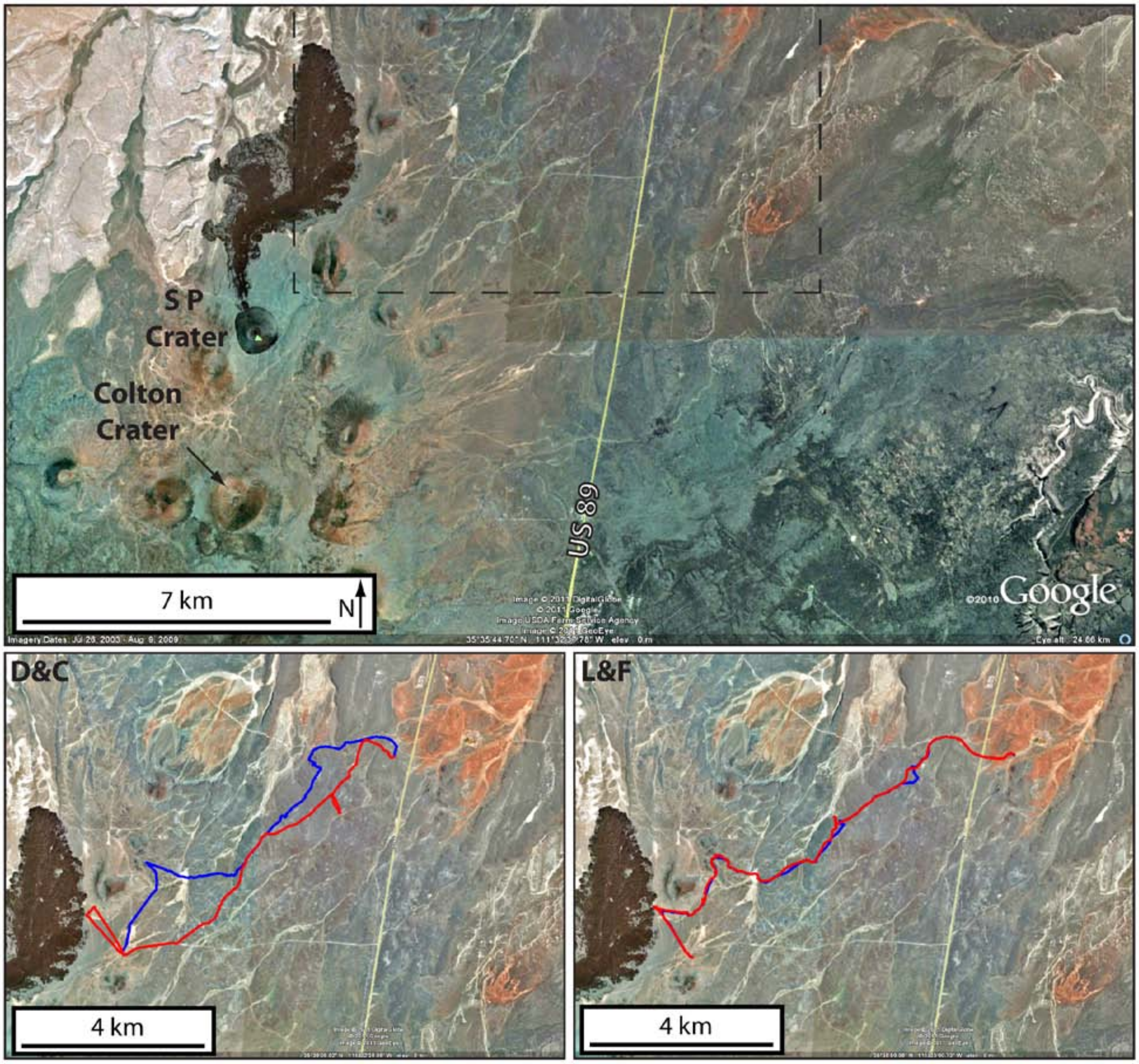

Figure 1.

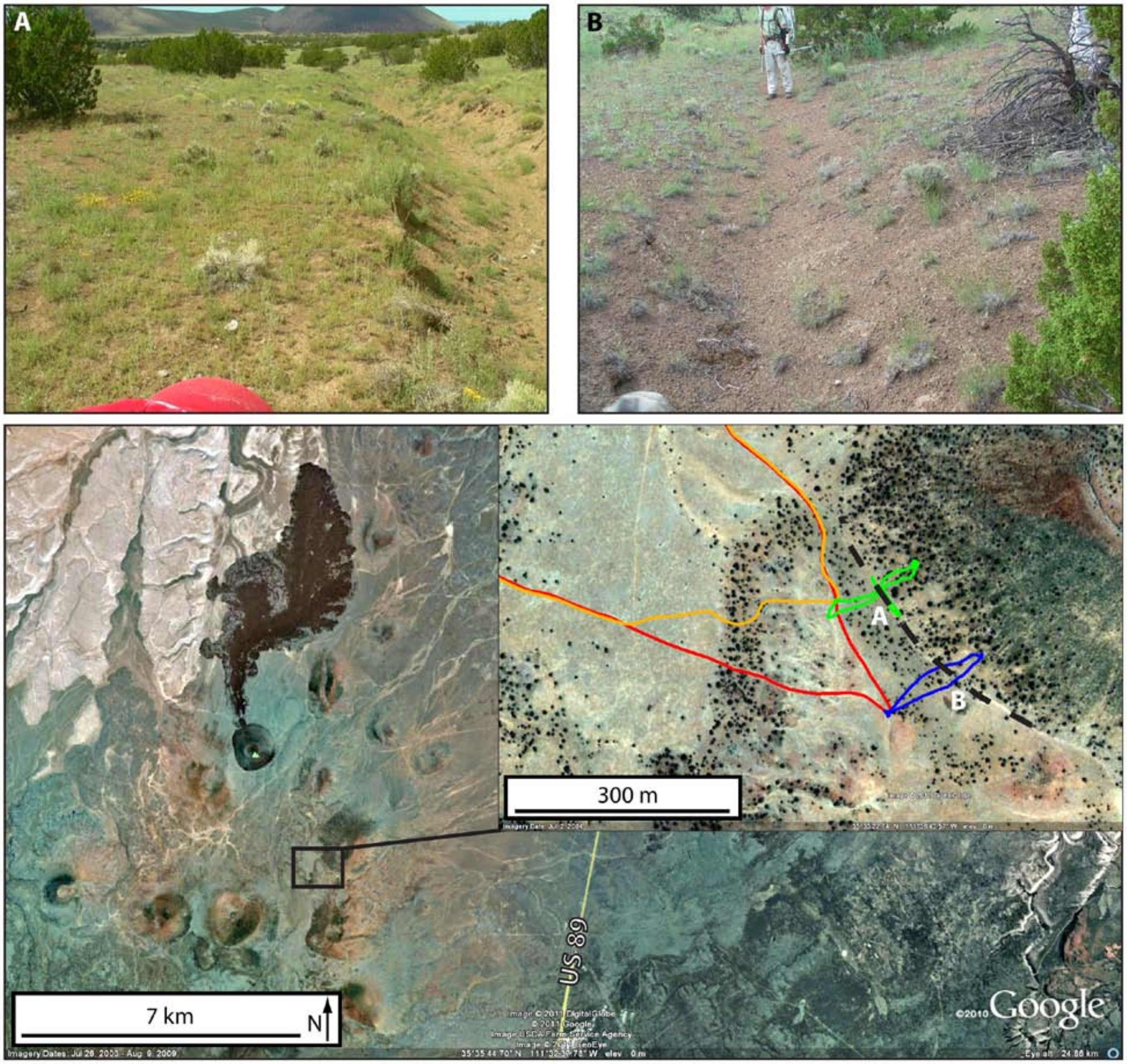

Figure 2.

Author Photos

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