Analysis of science team activities during the 1999 Marsokhod Rover Field Experiment: Implications for automated planetary surface exploration

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Abstract. This work analyzes the behavior and effectiveness of a science team using the Marsokhod mobile robot to explore the Silver Lake region in the Mojave Desert near Baker, California. The work addresses the manner in which the geologists organized themselves, how they allocated their time in different activities, how they formed and communicated scientific hypotheses, and the frequency with which they requested different types of data from the mission archive during the first 3 days of the mission. Eleven scientists from the NASA Ames Research Center and three of the five scientists who participated from their home institutions were videotaped as they worked throughout the 3-day experiment. The videotape record indicates that 46% of available person-hours were consumed in semistructured or formal meetings and that only 1% of their time was spent studying immersive, three-dimensional virtual reality models of the robot's surroundings. The remainder of their time was spent in unstructured work sessions in groups of two or three. Hypothesis formation and evolution patterns show a meager flow of information from the distributed science team to the on-site team and a bias against reporting speculative hypotheses. Analysis of the visual imagery received from the robot indicates that acquisition of the large panoramic information leads to high levels of redundancy in the data acquired. The scientists' archive requests indicate that small, specifically requested image targets were the most frequently accessed information. The work suggests alternative organizational structures that would expedite the flow of information within the geologic team. It also advocates emphasizing specific science targets over high-resolution, stereoscopic, panoramic imaging when programming a mobile robot's onboard cameras.

1. Introduction

Robotic geology, the identification of rocks and features via a remote, mobile robot, is a relatively new field of intellectual endeavor distinct from field geology, its closest relative. NASA's Mars Exploration program demands a high level of sophistication and insight into this scientific field if it is to succeed in discovering signs of life on Mars. In order to speed the growth of this field the NASA Ames Research Center has conducted a number of field tests with mobile robots in terrestrial, Mars-like environments.

During the next 5 years, NASA will send three robots to investigate the surface of Mars to find evidence of life. The challenge is daunting, even considering NASA's role as a world leader in robot technology and extraplanetary exploration and its access to many of the world's finest scientists and engineers. Robotic geology is just past its infancy. The first fossil discovered by a mobile robot on Earth or otherwise occurred during the Atacama Desert Trek in the summer of 1997 [Wettergreen et al., 1999].

The technical challenges of mobile robots and remote imaging systems used for geologic exploration include control with long time delays, imaging resolution, and restricted choices of sensors because of tight power and weight constraints. These challenges are magnified by the many differences between robotic geology and traditional field exploration. Field geologists readily move over terrain, easily select and closely examine rocks, and effortlessly switch their attention among different geological features. These needs are not easily met when using mobile robots. Field geologists can also employ senses, such as touch, taste, and smell [Compton, 1985], which cannot be done with mobile robots. Robotic systems, however, can provide a reliable archive of previously visited areas. These data may be quantitatively analyzed for shape, size, and color. Multiple images can provide context and detail on one screen. Image data may be coregistered with spectral analysis. The archive may be simultaneously presented to many geologists for opinions and insight. These challenges and opportunities of remote geology make it distinct from traditional field geology.

One of NASA's immediate needs is to maximize the scientific productivity of remote robot exploration in order to achieve the greatest possible benefit from the near-term Mars missions. To address this need, the NASA Ames Research Center has participated in a series of field trials with mobile robots in challenging remote environments. The trials have
been performed at the Kilauea volcano [Stoker and Hine, 1996]; at Mt. Spur, Alaska [Bares and Wettergreen, 1999; Fong et al., 1995]; under the Arctic glacial ice [Hine et al., 1994]; at Dinosaur Tracks, Arizona [Christian et al., 1997]; and in the Atacama Desert in Chile [Cabrol et al., 1998a, 1998b, 1998c]. In these tests a fielded robot is directed by a team of geologists and engineers to make scientific observations of the remote terrain. Typically, the centerpiece of the operator interface has been the generation and presentation of photorealistic virtual reality (VR) environments representing the robot's immediate surroundings [Christian et al., 1997; Durlach and Mayor, 1994].

With each iteration the team gains experience and develops new systems, procedures, tools, and technologies that have fueled the growth of the field of robotic geology, but progress tends to be haphazard and focused on the technical interests of the developers rather than programmatic needs.

Achieving even more rapid advancement requires an objective, scientific understanding of the process itself. This will help to guide innovation, gain understanding of the shortcomings of present methods, and define theoretical targets for maximum efficiency. The previous approach emphasized free creativity in the development of new tools and techniques inspired by informal observation of the field tests. The informality of the approach is inefficient in the face of complex confounding patterns caused by the differences between each test, which can lead to the misinterpretation of cause and effect relationships and the misunderstanding of important synergies. Group interviews, for example, often overemphasize immediate problems and de-emphasize more fundamental issues that often lead to systematic changes.

Unfortunately, few quantitative tools are available to measure scientific success or to compare one field test with the next. The process employed by scientists while investigating remote terrain is poorly understood and has not been described by any models, process flows, or specific performance measures. Field trial technology continually evolves by trial and error. Quantitative analysis techniques are necessary to extract the meaning and implications from this complex, dynamic environment and increase the efficiency of technological evolution.

This work details the activities of scientists during one field test, conducted in February 1999 in the Mohave Desert with the Maroskhod mobile robot. It characterizes the science team operations in order to understand how to design tools and systems that will maximize the effectiveness of robotic geology. The analysis identifies how the geologists, both in the control room and in distributed sites, organized themselves and performed the three main tasks of robotic geology: (1) building a scientific understanding of the remote terrain, (2) prioritizing scientific goals for future robot command sequences, and (3) preparing a list of specific tasks and data collection requests for the robot. This analysis begins a process that will ultimately lead to the quantification of scientific team performance.

2. Background

McGreevy [1992, 1994] is one of the few researchers who have considered the robotic geology process. In his 1992 paper, two geologists were monitored as they explored a natural geological site while wearing stereo cameras and a head-mounted display. Their investigation process was monitored with video recordings and interviews conducted by the investigator. McGreevy focuses on the manner in which a field geologist explores a site. The work follows an ethnographic protocol and attempts to provide insight into the process of exploration by analyzing the behavior, movements, and language of the geologists. Unfortunately, the work has limited immediate benefit for designers of software interfaces for robotic geology, because it is directed toward studying how geologists explore natural terrain in the field as opposed to exploring terrain through the various unique constraints and limitations of a robot.

A number of human factors studies have been conducted with workers to determine the effectiveness of new tools. The application areas of these studies include medicine [Lin et al., 1998], satellite operators [Charlton, 1992], and nuclear plant operators [Ohnaka et al., 1994]. Such studies identify and prioritize the specific cognitive and physical challenges faced by these expert workers. Once such challenges are identified, the researchers develop strategies to mitigate them. Solutions may include tool redesign, workload balancing, workspace redesign, and technological innovation. The work presented here seeks to introduce this type of analysis to the field of robotic geology.

Future Mars missions will be influenced by the cost and effectiveness of maintaining a science team at mission control during an extended mission. Effective tools that allow geologists to participate in a Mars mission from their home institution would ameliorate three important challenges: the physical separation of the geologists from familiar colleagues and reference materials; limitations on the number of geologists who can participate because of the relatively noisy and hectic environment of the control room; and possibly inappropriate influence of immediate mission demands relative to the pure scientific inquiry and objectiveness.

3. Methods and Procedures

Before the test was conducted, the science operations room was fitted with four cameras and four microphones suspended from the ceiling. The room was organized with a large conference table in the center, seven Macintosh computers on two sides, two Digital computers and two Silicon Graphics workstations on another side, one of which was connected to a large-screen television equipped for stereoscopic rendering, and a white board on the fourth side.

During the mission, 11 geologists worked in this room. Six more geologists participated in the test from their home institutions using Web-based technology and a conference phone. Three of these were videotaped at the University of Iowa's Graphical Representation of Knowledge (GROK) Laboratory. Observers specializing in human factors were present at both NASA's science team room and the GROK Laboratory throughout the 3-day experiment. After the first 3 days of experimentation the on-site scientists returned to their home institutions for an extended mission. This work focuses on the first 3 days of operations.

3.1. Summary of Activities

Table 1 presents a brief description of the main events that took place during the 3-day field test.
To estimate the total time spent in each activity for the scientists in the NASA control room, 174 sample frames were selected at 10-min intervals from the video tape record. Each scientist in the frame was assigned to one of six categories or as not present in the mission room. The six categories were VR models, panoramic, printouts/table, scientists working at computers during the meeting, scientists working at computers and working at the conference table with charts immediately after or before teleconferences with the main group, scientists working at computers and working at the conference table with charts directly addressed or when topics that they had studied were being discussed. They held independent teleconferences with the other members of the distributed science team, often immediately after or before teleconferences with the main group.

### Table 1. Main Activities

<table>
<thead>
<tr>
<th>Time</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0830-1030</td>
<td>Briefing session</td>
</tr>
<tr>
<td>1030-1215</td>
<td>Analyze panoramic and descent images. Plan first robot command sequence.</td>
</tr>
<tr>
<td>1215-1715</td>
<td>Refine rover position estimate, specify rocks for spectral analysis, name features. At 1545,</td>
</tr>
<tr>
<td></td>
<td>engineering team sends first command sequence.</td>
</tr>
<tr>
<td>1715-1922</td>
<td>Debrief. Define second robot command sequence</td>
</tr>
<tr>
<td>0830-1015</td>
<td>Group meeting discussing technical fault on the robot and weighing next course of action. Some</td>
</tr>
<tr>
<td></td>
<td>scientists work at computers during the meeting.</td>
</tr>
<tr>
<td>1015-1200</td>
<td>Informal work session. Telecon to debate next move.</td>
</tr>
<tr>
<td></td>
<td>At 1100 teleconference participants vote to move robot uphill to local source of white rocks. At</td>
</tr>
<tr>
<td></td>
<td>1145 the robot is repaired.</td>
</tr>
<tr>
<td>1200-1230</td>
<td>Teleconference to decide on specific robot program for next sequence.</td>
</tr>
<tr>
<td>1230-1800</td>
<td>Informal work session. TIMS image and new data from the robot become available at 1430. Science</td>
</tr>
<tr>
<td></td>
<td>team defines third command sequence at 1615.</td>
</tr>
<tr>
<td>1800-1925</td>
<td>Debrief with teleconference starting at 1830.</td>
</tr>
<tr>
<td>0815-1000</td>
<td>Team meeting. Debate future science objectives, plan for extended mission. Engineering team</td>
</tr>
<tr>
<td></td>
<td>announces that moving farther uphill is impractical.</td>
</tr>
<tr>
<td>1000-1100</td>
<td>Informal work session.</td>
</tr>
<tr>
<td>1100-1230</td>
<td>Teleconference meeting. New sequence 3 planned.</td>
</tr>
<tr>
<td>1230-1330</td>
<td>Informal work session.</td>
</tr>
<tr>
<td>1330-1530</td>
<td>Local meeting to debate science objectives and simulation objectives. Teleconference from 1500 -</td>
</tr>
<tr>
<td></td>
<td>1530 to summarize discussion and revise sequence 3.</td>
</tr>
<tr>
<td>1530-1730</td>
<td>Wrap up meeting.</td>
</tr>
</tbody>
</table>

The average time in each activity was 31% computer, 23% teleconference, 23% local meeting, 11% printouts/table, 3% panorama, and 1% VR models. A surprising 46% of the time, or 150 person-hours, was devoted to meetings. This amount is probably underestimated because some time in front of computers and working at the conference table with charts might be better categorized as a meeting. During their 148 person-hours of unstructured work time, the scientists strongly preferred to work with computers followed by computer printouts. This trend became more pronounced as the mission progressed, changing from a nearly equal distribution on the first day to a 4:1 preference on days 2 and 3. The extra use of printouts on the first day may have been caused by the availability of large descent image printouts, which received the greatest attention on the first day. Of the 9.3 person-hours spent observing the panoramic image, 8.2 occurred on the first day, as the scientists groped for an understanding of the robot's context and named relevant features. The 3 person-hours spent with the virtual reality display were roughly evenly distributed on each day and tended to occur when new stereoscopic panoramic images arrived or during discussions of trafficability. The time spent in activities may not correlate directly with the information gained from each information source but may be viewed as a measure of each scientist's preference in allocating time toward information sources perceived as providing the greatest insight into the problem that they sought to address.

The three members of the distributed science team who were video taped at the GROK Laboratory tended to adopt a less structured work style than the scientists at NASA. They generally arrived at designated teleconference times, pressed the mute button on the conference phone, studied images on the nearby computers, held conversations among themselves, and added comments through the conference phone when directly addressed or when topics that they had studied were being discussed. They held independent teleconferences with the other members of the distributed science team, often immediately after or before teleconferences with the main group. Between teleconferences they analyzed data from computers in their offices or in their homes.

### 3.2. Team Organization

The scientists at NASA divided themselves into three teams. Seven geologists identified themselves as members of the geomorphology team, three as members of the mineralogy team, and one as the exobiology team. The exobiologist was unable to participate in days 2 and 3 of the experiment. During the first day the distributed science team was treated as an independent group. During the second and third days the distributed science team was incorporated into the geomorphology team. The leader of the science team rotated with each day of operations, as did the leader of each scientific subgroup (with the exception of exobiology). One geologist who had extensive previous experience with robot geology served as liaison between the geologists and the engineering team housed in a room down the hall. The engineering team was ultimately responsible for sending commands to the robot.

During unstructured work periods the scientists typically worked in pairs or in groups of three. Membership in these subgroups was often consistent during the mission but occasionally varied depending on the interests of the individuals.
Two individuals tended to act as liaisons between groups or pursued ideas that were not covered by the team organization, such as defining new strategies for data collection or image analysis. When two subgroups interacted, they sometimes attracted the attention of other individuals, who then gathered for a spontaneous small group meeting. At other times group leaders initiated small group meetings in order to summarize ideas just before a full team meeting. Free exchange and discussion of ideas characterized spontaneous meetings. In contrast, arranged, formal meetings tended to work in a round-robin fashion with each subgroup presenting their findings followed by a brief question and answer session. In most cases, however, questions and discussion were relatively limited in the formal meetings.

3.3. Formation of Hypotheses

At the beginning of the mission the scientists were asked to keep logs of their activities and to list their hypotheses and confidence in those hypotheses as they were formed. Pairs and trios of geologists working together were the primary source of new hypotheses. While working in small groups of two or three, these scientists had quiet discussions while they worked. Often, their work focused on a specific task that they defined for themselves, such as cobble counting, matching rock outcroppings from two different viewpoints, or demarcating areas of differing trafficability. This work might be better classified as data exploration rather than hypothesis forming and testing. Often the statement of a clear hypothesis occurred only when group and team leaders requested specific
hypotheses and confidence estimates in order to fill out their questionnaire. The confidence estimates ranged on a scale from 1 (little confidence) to 5 (very confident).

Scientists working as individuals moved more rapidly between tasks and worked briefly with pairs of geologists to learn about intermediate results and to share knowledge gained from other scientists. Then they worked independently to explore a new idea or speculation. For example, one scientist worked closely with the system engineers to explore new strategies for using the robot and analyzing the data. These efforts seldom evolved into specific hypotheses on the final questionnaire and were more often incorporated into mission plans and suggestions for future improvements.

Table 2 summarizes the hypotheses made, as recorded in the handwritten science logs kept during the mission and from the notes taken during the summary briefings by the first author. Hypotheses 5-10 were adapted from e-mail notes written by the distributed science team and published on the Web by noon on the second day. The confidence values for these five hypotheses were estimated after the experiment was complete.

**Table 2. Hypotheses Recorded**

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Day</th>
<th>Confidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Two to four rock types</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2. Rover location within descent images</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>3. Rover pointing southeast</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>4. White rock outcrop and lower ridge are the same material</td>
<td>1</td>
<td>2.5</td>
</tr>
<tr>
<td>5. Layered sequence is a shoreline sequence of a lake</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>6. Layered sequence is an older alluvial fan/lake sequence</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>7. Descent images show a playa lake shoreline</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>8. Red tinted rock behind white rock altered silicic volcanic</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>9. Dark rock is a basaltic dike</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>10. Dark rock may be associated with hydrothermal alteration</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>11. Bright rocks are carbonates (dolomite and calcite)</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>12. Desert varnish coats dark rocks</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>13. Rock composition on which coating is varnish is quartzite</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>14. Identification of layering/banding in rocks</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>15. Carbonate detection works at 67% level</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>16. Rocks are coming from degradational fan</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>17. Location of rock sources</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>18. Light rocks most abundant in lander area are from two sources</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>19. Boba Fett Peak may have limestone and dolomite units</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>20. Valentine rock is quartz rich</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>21. Local white rock is distal exposure of Boba Fett</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>22. White rocks are carbonates</td>
<td>3</td>
<td>4.5</td>
</tr>
<tr>
<td>23. Dark rocks are coated with varnish</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>24. Light colored outcrop in mid-Boba Fett is limestone; brown material to immediate right is dolomite</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

Contrary to expectations, there was no significant increase in hypothesis confidence during the 3 days of the mission ($t = -1.29, p > 0.1$), with average confidence levels of 3.6, 3.6, and 4.0 for the three days. Three hypotheses were repeated from day 2 to day 3. The observation that desert varnish coats the dark rocks (hypotheses 12 and 23) goes from 4 to 3.5 from days 2 to 3. The observation that the white rocks are carbonates (hypotheses 11 and 22) degrades from 5 to 4.5 from days 2 to 3.

The scientists may manipulate the wording to mediate confidence levels. Compare, for example, the observations of Boba Fett Peak (hypotheses 19 and 24). Hypothesis 24 makes a much stronger statement regarding the composition of the peak (separating limestone from dolomite) than hypothesis 19, which states that the peak may show limestone and carbonate units. Both hypotheses have a confidence level of 4. There are no examples of conflicting hypotheses presented in the logs, except for hypotheses 5-6 and 9-10. These exceptions, however, were a result of the authors' interpretation of textural material that was not recorded as a hypothesis list. Also, only hypotheses 6 and 14 were speculative, with a confidence < 2.5.

The summary hypotheses listed at the end of the day by the on-site team did not include any of the observations made by the distributed team, possibly indicating a poor transference of ideas from the distributed to the on-site team. The limited access of the remote team's summary of observation by the on-site team (just one access during the 3 days, according to Web logs) also suggests a limited exchange of information from the distributed to the on-site science team. A particularly striking example of this phenomenon is the distributed science team's observation on the first day that the test site was at the edge of a playa. Members of the on-site team did not recognize this observation until the thermal infrared multispectral Scanner (TIMS) image became available late in the second day. The observation was not discussed as a group until 1300 on the third day. Self-censure because of the relatively long distance to the feature may have prevented earlier discussion of this potential science target.

**3.4. Communicating Data and Results**

Four different types of data were provided during the mission: primary data downloaded from the robot, secondary data in the form of descent images and the TIMS image, data products derived directly from the downloaded data, and analysis and commentary provided by the scientists. Table 3 summarizes the data downloaded from the robot, the time at which it was available on the mission Web site, the number of images included in each data set, and the number of times the data was accessed by a user. These Web hits, recorded by the Web server's log, provide a measure of the scientists viewing preferences and strategies for exploring the data. Web hits indicate the number of times the image was downloaded from the central server and provide the lower bound on the number of times the image was actually used, since individual machines may cache the images and users could save or print out specific images.

The measure of monoscopic redundancy in Table 3 estimates the number of times the same feature is imaged within a single data set. Highly redundant images cause more information to be transmitted than is needed and may cause researchers to be less attentive to individual images. The cal-
Table 3. Data Available to the Geologists Downloaded From the Robot

<table>
<thead>
<tr>
<th>Data</th>
<th>Image Type</th>
<th>Size, Mb</th>
<th>Time</th>
<th>Images</th>
<th>Average Hits/Image</th>
<th>Redundancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereo panorama of site 1</td>
<td>1/3-resolution</td>
<td>15.10</td>
<td>1800</td>
<td>1176</td>
<td>0.4</td>
<td>5.12</td>
</tr>
<tr>
<td></td>
<td>color stereo</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>full-resolution</td>
<td>0.03</td>
<td>1638</td>
<td>1</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>High-resolution image of white rock</td>
<td>full resolution</td>
<td>0.04</td>
<td>1652</td>
<td>1</td>
<td>39</td>
<td>1</td>
</tr>
<tr>
<td>High-resolution image of Acorn Hill</td>
<td>full resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panorama of site 1, jpeg format with quality factor of 0.75</td>
<td>full-resolution</td>
<td>24.55</td>
<td>1035</td>
<td>600</td>
<td>0.1</td>
<td>2.56</td>
</tr>
<tr>
<td>Images of spectral targets, ppm format</td>
<td>full-resolution</td>
<td>13.52</td>
<td>1113</td>
<td>15</td>
<td>9.1</td>
<td>2</td>
</tr>
<tr>
<td>Valentine rock</td>
<td>full-resolution</td>
<td>0.30</td>
<td>1334</td>
<td>1</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>High-resolution images of area near robot arm</td>
<td>full-resolutionmono</td>
<td>2.36</td>
<td>1805</td>
<td>12</td>
<td>4.2</td>
<td>1</td>
</tr>
<tr>
<td>Panorama from navigation cameras of site 2</td>
<td>b/w 1/3-resolution stereo</td>
<td>2.24</td>
<td>1805</td>
<td>64</td>
<td>0.7</td>
<td>3.64</td>
</tr>
<tr>
<td>High-resolution panorama of site 2</td>
<td>b/w full resolution stereo</td>
<td>8.62</td>
<td>0930</td>
<td>96</td>
<td>2.2</td>
<td>3.54</td>
</tr>
<tr>
<td>Stereo from navigation camera</td>
<td>b/w full-resolution stereo</td>
<td>0.07</td>
<td>1037</td>
<td>2</td>
<td>3.0</td>
<td>2</td>
</tr>
<tr>
<td>Color panorama of site 2</td>
<td>color, 1/3-resolution stereo</td>
<td>3.12</td>
<td>1200</td>
<td>224</td>
<td>0.4</td>
<td>3.83</td>
</tr>
<tr>
<td>Color images of spectral targets</td>
<td>color, full-resolution mono</td>
<td>1.68</td>
<td>1530</td>
<td>7</td>
<td>1.0</td>
<td>1</td>
</tr>
<tr>
<td>Color panorama of site 2 near rover arm</td>
<td>color, full-resolution mono</td>
<td>3.84</td>
<td>NA</td>
<td>39</td>
<td>NA</td>
<td>1.03</td>
</tr>
</tbody>
</table>

\[ R = \frac{n(h\text{fov})v\text{fov}}{\text{maxPan maxTilt} \int \frac{1}{\sin(\phi)\delta\phi\delta\theta}}, \]

where \( R \) is redundancy, \( n \) is the number of images in the sequence, \( h\text{fov} \) and \( v\text{fov} \) are the horizontal and vertical camera fields of view in radians, \( \text{maxPan} \) is the maximum pan angle of the camera plus \( h\text{fov}/2 \), \( \text{minPan} \) is the minimum camera pan angle minus \( h\text{fov}/2 \), \( \text{maxTilt} \) is the maximum tilt angle plus \( v\text{fov}/2 \), and \( \text{minTilt} \) is the minimum tilt angle minus \( v\text{fov}/2 \). Tilt ranges from 0 (straight up) to \( \pi \) (straight down). The formula calculates the redundancy independently of the step size between images and is appropriate as long as each feature in the mosaic range is imaged at least once. Redundancies larger than 2 are typically caused by step sizes at low tilt angles that cause large image overlaps.

The number of Web hits per image was inversely proportional to the redundancy of the data set, \( F(1,10) = 5.03, p < 0.05 \), indicating that less redundant data sets received the most attention. A simpler explanation, that the number of Web hits correlates with the size of the data set, is not supported. A regression of data set size versus Web hits was not significant, \( F(1,10) = 2.04, p > .05 \).

The secondary data sources include the descent images and the TIMS image. Both hardcopy and electronic versions of the six 1000 x 1000 grayscale pixel descent images were available to the geologists at the beginning of the experiment. The descent images were provided as raw data numbered 1-6 from highest to lowest altitude position. Images 1-5 were also provided with a rectangle indicating the position and orientation of the next lower resolution image. Images 4 and 5 were also provided with 10- and 5-m superimposed grids. The number of Web accesses for each type of image is provided in Table 4.

The TIMS image was placed on the Web at 1117 on day 2. This data was accessed 38 times during the primary mission. The image was supposed to have TIMS bands 1, 3, and 5 in blue, green, and red, respectively. However, when it was ini-

<table>
<thead>
<tr>
<th>Descent Image</th>
<th>Ground Resolution, m/pixel</th>
<th>Raw Image</th>
<th>Indicating Position of Next Image</th>
<th>With Overlaid Grid</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>2.79</td>
<td>12</td>
<td>0</td>
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<td>NA</td>
</tr>
<tr>
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<td>6</td>
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<td>13</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
typically performed navigation through these data sets. The
could be interactively viewed on a PC.

factor of 9. Lossy compression reduces the number of bits
compression. Decimation provides a subsampled set of
indistinguishable from the original.

factor of -8 and provided images that were nearly
quality factor of 75, which reduced the size of the image by a
image information, every third image pixel, for example,
mosaic to view the original data at full resolution. Stereo-
scopic imagery was processed into a three-dimensional view

stereoscopic imagery was also provided as an anaglyph color
mosaic and as a QuickTimeVR file [Kitchens, 1998] which
could be interactively viewed on a PC.

In order to conserve the amount of information transmitted
from the robot, the resolution of the image data was con-
trolled. Two approaches were used: decimation and lossy
compression. Decimation provides a subsampled set of
image information, every third image pixel, for example,
which reduces the resolution by a factor of 3 and file size by a
factor of 9. Lossy compression reduces the number of bits
required to store the image but may reduce the quality of the
image. Many of the images were jpeg compressed with a
quality factor of 75, which reduced the size of the image by a
factor of -8 and provided images that were nearly
indistinguishable from the original.

Two sets of data were provided on the first day of opera-
tions. The first displayed a panoramic view of the initial site
with a sequence of 538 stereo image pairs collected with the
PanCam system at adjacent pan and tilt angles [see Stoker et
al., this issue]. This data was decimated and jpeg compressed.
The data were provided in six formats: a large, color pano-
ramic poster; individual images; a clickable, miniature mo-
saic; an anaglyph mosaic; a three-dimensional model; and a
QuickTime VR model, which was available on the second
day.

The panorama mosaic was hit 27 times. The 27 subimages
within this mosaic were selected an average of 7.7 times each.
The associated anaglyph was hit 3 times. Scientists requested
274 of the 1176 individual images from the left and right
cameras comprising this mosaic between 1 and 19 times, with
an average of 1.73 accesses.

Because of a technical fault with the camera motor on the
morning of the second day, the geologists were provided with
600 higher-resolution versions of the original site 1 images,
undecimated, with jpeg compressed. The views provided by
these data were exactly the same as the views provided in the
first panoramic data set, but with different resolution param-
ters. Once the robot was repaired, the geologists received a
set of 15 images of the requested spectral targets and a close-
up image of the rock named Valentine taken with the arm-
mounted camera. Then the robot moved and provided a 1/3-
resolution stereo, black-and-white image of site 2 and a full-
resolution, monocular color image of the area within reach of the
robot arm.

On the second day, nine QuickTime VR models of the
original panoramas also became available. The three naviga-
ble panoramic views, in which the user can look around the
environment from a fixed perspective, were accessed 3, 9, and
25 times. Five object movies, in which interactions rotate the
object on the screen, were created for the rocks: Emperor,
Luke, Vader, Valentine, and Yoda. These object movies were
accessed 3, 2, 3, 4, and 6 times, respectively

On the third day the robot provided a high-resolution,
black-and-white panorama, 91 color 1/3-resolution images,
two images from the navigation camera, and seven images of
regions imaged by the near-infrared spectrometer. The black-
and-white panorama images were provided as left camera and
right camera mosaics and as an anaglyph, which were hit 16,
3, and 1 times, respectively. The 89 of the 90 original navi-
gation images were accessed between 1 and 11 times, with an
average of 2.37 hits each. Eleven of the 14 submosaics of the
navigation camera mosaics were accessed between 1 and 3
times with an average of 1.64 hits. The 1/3-resolution color
images were provided as left and right mosaics and a color
anaglyph, which were accessed 12, 0, and 2 times, respect-
ively. Four of the 6 submosaics were accessed for the left
camera mosaic; none of the other submosaics were hit. Only
61 of the 112 original images were accessed; these between 1
and 4 times, with an average 1.48. Four of the seven near in-
frared images were accessed: one once and the others 2 times
each.

The scientists’ selection pattern for image data is evident in
the four cases where full-resolution data could be accessed as
a submosaic or in individual image form. Full-resolution
submosaics were accessed a total of 227 times, compared
with 816 accesses of the individual images. However, 85%
of the total submosaics were accessed at least once, compared
with 53% for the individual images.

3.5. Analysis Tools

The tools provided for the geologists to conduct their in-
vestigation consisted of a variety of writing instruments, ace-
tate overlays, photo-manipulation software, measuring tools
within the three-dimensional software visualization toolkit,
printers, and scanners. With the exception of the three-
dimensional interface, all of the tools were used for various
analyses. Lack of training may have limited the use of the
three-dimensional interface.

3.5.1. Demarcating regions. One pair of geologists spent
~2 hours preparing acetate overlays on the descent images to
demarcate the areas of differing trafficability by the robot in
each area. These geologists compared the panoramic view
with the descent images to determine the size of obstacles and the
morphology of the ground to identify safe, risky, and im-
passable areas for the robot. The maps with the acetate
images were then scanned and placed on the project Web site.

Another pair of researchers used an image-editing tool and
the computer mouse to demarcate images and label the rocky
outcroppings. The resulting data product was immediately
posted on the Web site.

3.5.2. Comparing different sources of information.

Several subgroups spent considerable effort comparing, side
by side, pairs of images such as the descent imagery with the panorama, the TIMS image with the descent imagery, and views of identical features taken from two robot positions. This analysis enabled the researchers to determine the current robot location to within ~2 m, determine distance, heading, and scale of various features such as rocky outcappings or the lake shore, and estimate the shape of features (cliff or slope).

3.5.3. Cobble counting. The number, size, and shape of rocks in the immediate vicinity of the robot were analyzed at two robot positions to determine the number of different rock types, their age, and weathering patterns.

3.5.4. Spectroscopy. Near-infrared and midinfrared spectrographic analyses were performed on selected rocks and outcappings throughout the experiment by a pair of researchers who were almost solely occupied with this task. This analysis provided the chemical composition of the rocks and outcappings, which allowed the geologists to demarcate and identify different rock types.

3.5.5. Study of individual data sources. Several geologists studied each mosaic to develop an understanding of the local typography and the surface characteristics of nearby rocks. Color mosaics provided distinction among rock types by shape and color.

3.5.6. Labeling data. The geologists named the most prominent features with a convention of characters from "Star Wars," although some features had already been named before this convention was established. The labeling of features was focused on features identified in logs, rocks targeted for rock collection, and spectrographic analysis. The names were first placed on Post-It Notes™ on the panoramic image at the end of day 1 and were added to the electronic version of the panorama and placed on the Web by day 2.

4. Discussion and Conclusions

On the basis of time spent in activities, the area in which improvements are likely to have a large impact on overall robotic geology performance is team organization and communication, as evidenced by 46% of person-hours being devoted to meetings. The next most important issue is the tools and processes used to collect and interpret the data, which consumed 41% of the person-hours.

4.1. Team Organization and Communication

The person-hours analysis indicates that ~150 person-hours were used in team meetings. Because only one person can effectively communicate at a time at a team meeting, and because the number of new ideas generated during these meetings was relatively low, ideas may be more effectively communicated and debated during unstructured work activities. One time consuming activity in the team meetings was the discussion of the robot capabilities, including the size of various data sets and the specification of robot command sequences. These tasks were unfamiliar to the geologists. Because of the detailed knowledge and intuition required, it may be that only the robot developers and engineers will ever be able to accurately gauge the trafficability of an area or produce an optimal command sequence. It may be beneficial to use the team of geologists to prioritize specific scientific goals and assign the specification of the robot command sequence to a subgroup containing engineers familiar with the specific strengths and limitations of the robot.

The team organization does not emphasize the presentation of hypotheses and supporting evidence in the same time frame that decisions must be made. The main summary of hypotheses occurred at the end of the day, Pacific time, which was too late for the east coast participants to take part in the meeting. Consequently, the distributed group was not able to offer their findings or hear a detailed version of the evidence leading to various conclusions. Each morning the distributed team received a very brief verbal review of the previous day's finding and presented their ideas to a group that had already formed a consensus opinion. This approach may be responsible for the general exclusion of hypotheses formed by the distributed team in the team hypotheses summary generated each even??ing. This bias tended to demoralize the distributed team and resulted in several important ideas being overlooked by the local science team. One example is hypotheses 5 and 7 from Table 2 regarding the presence of a playa lake. The distributed team formed these hypotheses during the first day and published them on the Web site by the afternoon of the second day. The local team did not actively debate this hypothesis until the third day.

One approach to alleviate this problem would be for all of the scientists or small groups of scientists to publish their hypotheses, supporting arguments, and evidence on the Web at the end of each day. The summary meeting could be held the following morning, rather than at the end of the day. That way, all scientists could participate in the debate and would have the opportunity to prepare dissenting opinions before the summary meeting.

Another strategy is to separate the functions of hypothesis formation and science goal prioritization. With this strategy the scientists would work in cells of two or three to generate, critique, and publish hypotheses. A second team, possibly composed of representatives of each cell, would compare published hypotheses to form an ordered list of possible robot activities. This approach would allow most of the scientists to concentrate on the development of valid hypotheses, eliminating the overhead of large group meetings. The process would also place a greater emphasis on the consideration of all available hypotheses, rather than emphasizing those hypotheses developed by scientists physically in the meeting, as does the current process. Finally, this process of posting hypotheses and supporting and disconfirming evidence on the Web generally mirrors the well-established practice of scientific research, except that it accelerates the process to cycles of the order of hours rather than months.

A third possibility is that hypothesis statements are not the most appropriate organizing structure for communicating the current thinking of the scientists. Alternative organizational approaches might emphasize geologic maps or process storyboards.
entered into the archive by the geologists was placed either in the scientist's individual subdirectory or into group folders. This information was not searchable. To see what information was available, the scientists needed to periodically peruse many possible filing locations. These storage issues affected the scientist's opportunity to examine all available evidence before forming an opinion. This factor may account for some of the hesitancy the scientists exhibited in forming hypotheses.

4.2.2. Selection of Acquired Data. The analysis of Web hits indicates that not all data received equal attention. Particularly evident was the limited number of times three-dimensional data was accessed, either in the VR model or in the anaglyph mosaics or the QuickTime VR files available on the Web. The acquisition of three-dimensional data effectively doubles the amount of data that must be transmitted from the robot. Thus the cost in terms of data size was high with respect to the degree of use. In sharp contrast is the important impact the spectrophotographic analysis had on the interpretation of the landing site. The TIMS image as well as the NIR and TIR spectral data on rocks and regions were accessed frequently and contributed extensively to the hypotheses formed by the science teams [see De Hon et al., this issue].

There was general consensus that higher-resolution imagery would be profoundly important in the interpretation of the scene. As discussed by Grin et al. [this issue], one of the principal flaws in the remotely determined geology interpretation was that the dark rocks in the Boba Fett - Acorn Hill area were interpreted to be altered basaltic dikes or sills rather than amphibolites. Basaltic rocks and amphibolites have similar chemical compositions. Amphibolites can be identified by recognizing the contrasting presence of light minerals (plagioclase) and dark minerals (hornblende and biotite) with average diameters of 1 mm or less. In contrast, basaltic and shallow basaltic intrusions commonly have a relatively featureless and dark colored matrix. The ground-truth team readily determined that the rocks were amphibolites by observing the contrast between the light and dark minerals with their unaided eye while standing at the landing site, whereas the science team was not able to do this using the high-resolution individual images made available during the field test.

The three-dimensional information should be captured only in order to navigate the robot or where specifically requested by the geologists. Medium- to low-resolution panoramic images may be sufficient for the geologists to specify regions of particular interest. These regions could then be imaged in greater detail during the next command cycle. In general, the process should be defined around targets of specific interest to the science team, rather than the collection of generic, wide-field-of-view models.

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