AUTONOMOUS ROVER SCIENCE IN THE FIELD: YELLOW CAT. E.Z. Noe Dobrea[1], C. Ahrens[2], M.E. Banks[2], E. Bell[2], A. Breitfeld[3], T. Bristow[4], A. Candela[3], R.N. Clark[1], M. Hansen[3], A. Hendrix[1], G. Holsclaw[5], P. Knightly[6], N. Kumari[7], M.D. Lane[8], A.C. Martin[9], M. L. Meier[10], R.V. Patterson[11], N.C. Pearson[1], T.H. Prettyman[1], A. V. Steckel[5], S. Vijayarangan[3], F. Vilas[1], D. Wettergreen[3], S.P. Wright[1] - [1]Planetary Science Institute, 1700 East Fort Lowell, Tucson, AZ – eldar@psi.edu, [2]NASA GSFC, Greenbelt, MD, [3]Carnegie Mellon University, Pittsburgh, PA, [4]NASA Ames Research Center, Moffett Field, CA, [5]Laboratory for Atmospheric and Space Physics, U. Colorado, Boulder, CO, Department of Geosciences, [6]Department of Astronomy and Planetary Science, Northern Arizona University, Flagstaff, AZ, [7]Stony Brook University, [8]Fibernetics LLC, Lititz, PA, [9]Deptment of Physics, University of Central Florida, Orlando, FL, [10]Department of Environmental Science, University of Idaho, Moscow, ID, [11]Department of Earth and Atmospheric Science, University of Houston, Houston, TX,

Introduction: The autonomous science rover project of the Toolbox for Research and Exploration (TREX), a NASA SSERVI node, is exploring how a rover capable of science autonomy can improve the science yield and operational efficiency of telerobotic exploration and of astronaut/robot collaborative exploration. Central to our investigation is the concept that, given a set of driving hypotheses, a robotic explorer should be able to plan and execute traverses and observations to address these hypotheses while requiring little to no input from outside operators. Periodically, or when the robotic explorer encounters circumstances that fall outside the realm of expected observables, the robotic explorer contacts the operator to offer updates or request new directions.

Approach: We have developed and integrated a set of tools and techniques to enable a rover to constrain the geological origin(s) of a site on the basis of mineralogy. These tools include the hypothesis map [1,2], Tetracorder [3-5], and the Geologic Origins Table. A description of the approach is given in [6, 7]; recorded presentations describing the approach are given in [8, 9]; a description of our first field season testing these tools and techniques is given in [10].

Here, we describe our second season of field-testing the rover with autonomous science capabilities.

Objectives: The overall project objectives of the field experiment were to:

- Compare the operational efficiency and science yield of a semi-autonomous rover and of astronaut/rover collaboration with the standard exploration strategy.
- Test new exploration strategies that take advantage of rover autonomy.

Experiment: Three operational scenarios were executed for comparison purposes: 1) standard rover exploration paradigm, 2) autonomous rover exploration, and 3) astronaut/rover collaborative exploration.

The analysis and decision making tools were integrated onto the Carnegie Mellon rover, Zoë. A rover-mounted VNIR (0.35 – 2.5 μm) spectrometer and a hand-held FTIR (4 – 15 μm) were used to acquire spectra of targets for analysis by the rover and the science team. Five ride-along instruments were also used to collect data but were not used by the rover for interpretations: a rover-mounted Gamma Ray Spectrometer, a second handheld VNIR spectrometer, a handheld UV spectrometer, a micro-imager, and a portable XRD.

A science team was tasked with identifying science objectives and activities to be performed during the field experiment, with generating the hypothesis map that served as the rover's science guide, and with providing analyses and scientific conclusions for each of the three scenarios. The science team consisted of experts with accumulated experience in Gamma-ray spectroscopy, UV to mid-IR (0.2 to 14 μm) reflectance spectroscopy of solar system objects, and X-ray diffraction. The rover was commanded by the science team from a science operations center in Green River, UT. A field geologist was tasked with to performing a parallel investigation of the geologic history of the site for comparisons to the rover exploration scenarios.

Field Site: The field site was located in Yellow Cat, UT (38°51'19.73"N, 109°32'44.50"W). It was selected for its accessibility, traversability, preponderance of fine-grained materials, and scientific interest. The Yellow Cat Flat field area consisted of three main geologic units: the Cretaceous Yellow Cat member (Kcmy) of the Cedar Mountain Formation, the Jurassic, Brushy Basin Member of the Morrison Formation (Jmb), and the Jurassic and the Saltwash Member of the Morrison formation (Jms). Of these three units Jmb dominated the central portion of the field area. It generally consisted of flat lying montmorillonitic clays with lenses of chert, sandstone and siltstone. In the far southwest portion of the field area there were also outcrops of conglomerates. Kcmy mainly formed cliff walls in the North and Northwest portions of the field area and consisted of alternating beds of siltstone, sandstone and claystone. This material was mainly experienced by our investigation as float near the edges of the valley. JMS was located mainly in the Southeast portion of the field area and was made up of resistant, fine grained, quartz arenite sandstones that overlay siltstone. Within the field area were several uranium mines and veins of amorphous silica suggesting low grade mineral alteration had taken place [11].

Operational scenarios:

Scenario 1 - Standard exploration paradigm: In this scenario, the science team defined a set of science stops that they wanted the rover to visit. The rover acquired data with the rover-mounted spectrometer and the GRS while transiting between stops as well as at each one of the stops. Also at each stop, the science team identified targets of interest, which were measured with the entire instrument complement. The data was sent to the science team, which then analyzed and discussed the data, and decided on the next steps.

Scenario2 - Autonomous science rover: In this scenario, the science team provided the rover with a hypothesis map and related uncertainty map, and a list of desired target science stops. The hypothesis map was prepared using hyperspectral data from the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), as well as high resolution (< 1 m/pixel) images of the site. It was represented by a 3-dimensional data cube consisting of 10 stacked maps, with each layer representing a different geologic origin. For any position on the map, a 10-element vector encoded the relative probability of each geologic origin. Potential geological origins were established on the basis of mineralogy. Likelihood of a geologic origin was established by the number of minerals found at a location having a common origin. A map characterizing the uncertainty associated to the geologic origin at each location on the map accompanied the hypothesis map, where the number of potential geologic origins attributed to a mineral detection was used to establish uncertainty in geological origin.

Given the hypothesis map and associated uncertainty map, the rover established the region of highest uncertainty within a prescribed range as the next science stop. If a desired target science stop existed within the range, it was prioritized as the next science stop. As the rover traversed to the science stop, it acquired spectra with its on-board spectrometer and once at the science stop, the instrument suite was used to acquire complementary measurements on a set of random targets near the rover. The VNIR and FTIR data were interpreted to mineralogy and geological origin by the rover, which then used this information to update its hypothesis and uncertainty maps, and plan the next science stop. The data from the rest of the instruments was delivered to the science team. At the end of the day, the science team used the updated hypothesis map and the complementary measurements to assess the new hypothesis map and update for use on the following day by the rover.

Scenario 3 - Astronaut/rover collaborative exploration: In this scenario, we tested ways in which astronaut EVAs could benefit from autonomous rover capabilities to maximize EVA scientific return and reduce astronaut risk. In this scenario, simulated astronaut extravehicular activity (EVA) was coordinated with autonomous rover operations similar to those performed in Scenario 2, with predetermined locations to rendezvous with the astronauts for measurement and interpretation of astronaut-collected samples using the rover's instruments and Tetracorder module. The astronauts were assigned science stops, activities, and science questions to be addressed for each EVA that were intended to augment the rover collected data by: 1) investigating locations inaccessible to the rover, 2) providing overall contextual and stratigraphic observations/images, and 3) performing tasks not possible with rover instruments (i.e. digging, collecting samples).

Conclusions: We assessed how science yield and operational efficiency varied between scenarios. Predictably, the operational efficiency of the autonomous science rover was significantly greater, accomplishing in a few hours what was accomplished with the standard exploration paradigm in days. Given similar time frames, the autonomous rover was able to visit more science stations, and acquire more data.

The greatest science yield was provided by the astronaut/rover collaborative exploration. Collectively, the astronaut/rover capabilities better enabled real-time evaluation and facilitated impromptu adjustments to astronaut tasks and EVA path, as directed by the remote science team, based on the combined information and results. This shared task methodology maximized EVA efficiency and decreased crew risk by reducing overall EVA time. Also, the rover provided redundant capabilities for navigation (i.e. within astronaut line of sight, the rover was used to navigate to rendezvous or other locations), and communications (e.g. served as a relay between the science team and astronauts when topography limited primary communications).

Acknowledgments: This work was supported by SSERVI16 Cooperative Agreement NNH16ZDA001N (TREX).

References: [1] Thompson, D. R., *et al.* (2011) *J. Field Robotics, July / August*. [2] Candela, A., *et al.* (2017) *IEEE Intl. Conf. on Intellig. Robots and Systems.* [3] Clark, R.N., *et al.* (2003) *JGR* Vol. 108(E12), 5131. [4] Clark, R. N., *et al.* (2010) *JGR*, 115, E10005. [5] Clark, R. N., *et al.* (2012) *Icarus* 218 [6] Noe Dobrea, E. Z., *et al.* (2021), *LPSC 2021 # 2371.* [7] Clark, R.N. *et al* (2022) *LPS LIII* # 2323 [8] Noe Dobrea, E.Z. *et al.* (2019), *NESF 2019* https://youtu.be/W83Mp5yOkxY [9] Noe Dobrea, E.Z. *et al.* (2020), *NESF 2020* https://youtu.be/CyH5qgz0Wb0 [10] Noe Dobrea, E.Z. *et al.*, (2022), *NESF 2022* [11] Doelling, H.H. and Kuehne, P.A. (2014) *Utah Geol. Survey, Map 259DM.*