Automated Targeting for the MER Rovers[1]

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Abstract— The Autonomous Exploration for Gathering Increased Science System (AEGIS) will soon provide automated targeting for remote sensing instruments on the Mars Exploration Rover (MER) mission, which currently which currently has two rovers exploring the surface of Mars. Currently, targets for rover remote-sensing instruments, especially narrow field-of-view instruments (such as the MER Mini- TES spectrometer or the 2011 Mars Science Laboratory (MSL) Mission ChemCam Spectrometer), must be selected manually based on imagery already on the ground with the operations team. AEGIS enables the rover flight software to analyze imagery onboard in order to autonomously select and sequence targeted remote-sensing observations in an opportunistic fashion

In this paper, we first provide some background information on the larger autonomous science framework in which AEGIS was developed. We then describe how AEGIS was specifically developed and tested on the JPL FIDO rover. Finally we discuss how AEGIS will be uploaded and used on the Mars Exploration Rover (MER) mission in early 2009.

TABLE OF CONTENTS

1. INTRODUCTION.....1
2. OVERVIEW OF THE OASIS SYSTEM.....2
3. FEATURE AND EVENT DETECTION.....3
4. SCHEDULING OPPORTUNISTIC SCIENCE.....4
5. AUTONOMOUS TARGET SELECTION AND SAMPLING.....5
6. AUTOMATED TARGETING ON MER ROVERS.....6
7. SUMMARY.....7
8. ACKNOWLEDGMENTS.....8
REFERENCES.....8
BIOGRAPHY.....ERROR! BOOKMARK NOT DEFINED.

1. INTRODUCTION

The Mars Pathfinder (MPF) and Mars Exploration Rover (MER) missions have demonstrated that mobile rovers are a viable and productive option for exploring the surface of other planets. The MER rovers have traveled over many kilometers of terrain and survived harsh planetary conditions, including Martian winters and major dust storms, to continue collecting data. The extensive scientific observations collected have uncovered profound new insights into Mars' current and past environment, the history of its rocks and the various roles and abundances of water.

Surface rovers offer scientists the ability to move around a planetary surface and explore different areas of interest. The farther the rover can travel, the greater the opportunity for scientific discovery. Due to advances in rover navigation, traverse distances are increasing at a rate much faster than communications bandwidth. While the Sojourner rover traveled around 100m in the entire mission, the MER rovers have now traveled combined over 20 kilometers. Further long traverses are becoming commonplace on MER. Currently the MER Opportunity rover is trying to reach a new scientific target – the Endeavour crater (shown in Figure 1). The distance to Endeavour (~12 kilometers) is almost as great as the total distance Opportunity has traveled since landing in 2003. Many long drives will be used to reach this target in a reasonable time frame.

As this trend in increased mobility continues, the quantity of data that can be returned to Earth per meter traversed is reduced. Thus, much of the terrain the rover observes on a long traverse may never be observed or examined by scientists. This paper discusses a system developed to autonomously recognize and characterize high value science targets during and after drives without requiring large amounts of data to be transmitted to Earth.

The Autonomous Exploration for Gathering Increased Science System (AEGIS) will provide automated targeting for remote sensing instruments on the Mars Exploration Rover (MER) mission. Currently, targets for remote sensing instruments, especially narrow field-of-view instruments (such as the MER Miniature Thermal Emission Spectrometer (Mini-TES) or the 2009 MSL Laser-Induced Remote Sensing for Chemistry and Micro-Imaging (ChemCam) spectrometer) must be selected manually based on imagery already on the ground with the operations team. AEGIS will enable the rover flight software to analyze imagery onboard in order to autonomously select and sequence *targeted* remote-sensing observations in an opportunistic fashion. AEGIS operates by analyzing MER

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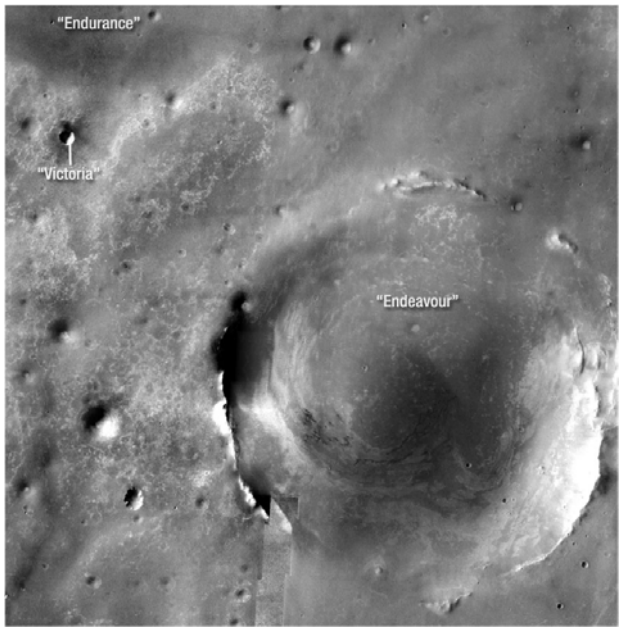

Figure 1 – Endeavour crater on Mars. Currently the Opportunity rover is en route to Endeavour, which is over 12 kilometers (or 7 miles) away from Opportunity's current position, which is near Victoria Crater. To reach this target in a time of several years, many long drives will be needed.

navigation camera images to identify terrain features of\ interests such as rocks with certain characteristics. The type of terrain characteristics to target is specified by scientists on the ground during the sequencing process. For example, scientists could request measurements of large rocks with light albedo (i.e, lightly colored). Once a target is identified in a navigation camera image, its location is determined and a remote sensing instrument is re-targeted at that location to take an additional measurement of the interesting target. This capability can be run during and after rover traverses when the rover has driven into a new terrain area and no imaging of the area has yet been downlinked to Earth. This capability is especially useful for multi-sol (i.e., multi-day) plans where a drive is performed on the first sol and only untargeted remote sensing can be performed on the second and third sols since another communication cycle with Earth has not yet occurred. Since the MER Mini-TES spectrometer is no longer functioning on MER Opportunity rover and is expected to have only a few remaining measurements on the Spirit MER rover, the AEGIS capability will be illustrated by taking sub-framed, 13 filter, high resolution images with the MER Panoramic cameras. Currently AEGIS is planned for upload to the MER rover in Spring of 2009.

In this paper we first provide an overview of the underlying autonomous science framework in which AEGIS was developed. We then describe how AEGIS was originally designed through this framework and how it was tested on the JPL FIDO rover. We then provide details on how it will be used on the MER rover mission.

2. OVERVIEW OF THE OASIS AUTONOMOUS SCIENCE FRAMEWORK

The AEGIS capability was developed as part of a larger autonomous science framework called OASIS (Onboard Autonomous Science Investigation System) [1]. OASIS is designed to operate onboard a rover identifying and reacting to serendipitous science opportunities. OASIS analyzes data the rover gathers, and then using machine learning techniques, prioritizes the data based on criteria set by the science team. This prioritization can be used to organize data for transmission back to Earth and it can be used to search for specific targets it has been told to find by the science team. If one of these targets is found, it is identified as a new science opportunity and a "science alert" is sent to a planning and scheduling system. After reviewing the rover's current operational status to ensure that it has enough resources to complete its traverse and act on the new science opportunity, OASIS can change the command sequence of the rover in order to obtain additional science measurements. A large amount of work in OASIS has been done to identify and characterize terrain targets such as rocks within images, which will be used as the primary science focus for the rest of this paper. However, OASIS has been applied to analyze data from other instruments (e.g., spectrometers) as well as atmospheric targets. For example, OASIS can currently identify dust-devils and clouds in images as part of the current MER rover onboard software [2].

A breakdown of OASIS capabilities is shown in Figure 2. There are three major components that comprise OASIS:

- **Extract Features from Images:** Enables extraction of features of interest from collected images of the surrounding terrain. This component both locates terrain targets (e.g., rocks) in the images and extracts properties of those targets including shape, texture, size, and albedo.

- **Analyze and Prioritize Data:** Uses the extracted features to assess the scientific value of the planetary scene and to generate new science objectives that will further contribute to this assessment. This component consists of several different prioritization algorithms that analyze the collected data and prioritize the terrain targets. A new set of observation goals is generated to gather further data on targets that either conform to the pre-set specifications by the science team, or are so novel in comparison to other terrain features, that another data measurement may be required.

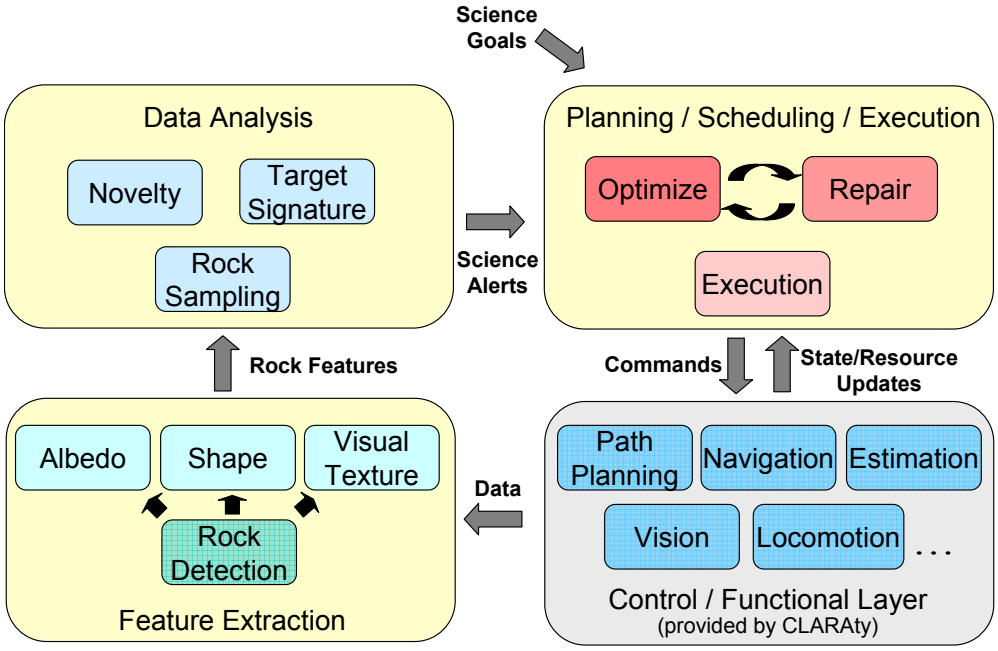

Figure 2 – OASIS (Onboard Autonomous Science Investigation System) framework. This diagram shows how different decision-making capabilities interact within OASIS (shown in the yellow boxes) and how OASIS interacts with low-level robotic control software (shown in the gray box).

- **Plan and Schedule New Command Sequence:** Enables dynamic modification of the current rover command sequence (or plan) to accommodate new science requests from the data analysis and prioritization module. A continuous planning approach is used to iteratively adjust the plan as new goals occur, while ensuring that resource and other operation constraints are always met.

The next few sections provide more details on OASIS functionality that directly supports autonomous targeting capabilities.

3. Feature and Event Detection

OASIS uses a number of different methods to analyze data gathered by a rover. For autonomous instrument targeting, this data has been primarily terrain image data taken by rover cameras.

Terrain Target Detection

One important focus of OASIS has been detecting interesting terrain targets such as rocks in grayscale images. For autonomous targeting these images are typically from rover navigation cameras. One commonly used method, called Rockster, focuses on intensity edges in grayscale imagery [3]. Rockster initially locates partial boundary contours of rocks using a procedure similar to the Canny edge detector. In particular, an intensity gradient is calculated over the image; ridges in the intensity gradient are linked together using non-maximum suppression, hysteresis thresholding and edge-following yielding a set of raw contours.

This initial set of contours does not directly provide a usable segmentation of the rocks from the background due to various problems, including: spurious contours from the sky-ground boundary (horizon line) and texture within individual rocks and the background. Rockster attempts to resolve these problems by splitting the initial contours into low-curvature fragments. Potential T-junctions that were missed by the edge detector are identified and used to further split fragments into even smaller pieces. A gap-filling mechanism is then applied to add new contour fragments between existing fragment endpoints. The final step is to regroup the edge fragments into coherent contours, which is accomplished through background flooding.

For automated targeting of limited FOV instruments, it is important that only true targets are considered for targeting. Thus for this application, Rockster is run in a mode that reduces false positives however also has the effect that fewer overall targets are found. This behavior is a trade-off that can be adjusted depending on the application. It could be judged for some application that is it more important to find a larger percentage of overall targets at the risk of returning false positive (i.e., non-interesting targets) more often.

Feature Extraction

Once terrain targets are identified in an image, the OASIS system classifies their physical properties. The properties that OASIS estimates for autonomous targeting are albedo, size, and several variants of shape. The albedo of a rock is an indicator of the reflectance properties of a surface. OASIS measures albedo by computing the average gray-scale value of the pixels that comprise the image of the rock.[2] The reflectance properties of a rock provide information about its mineralogical composition.

One of the most important properties of rocks on the surface is their size. Size can be used to identify sorting and geologic contacts. We model rocks as ellipses (if no range data is provided) or ellipsoids (if range data is available).

Although the shape of a rock is complex and often difficult to describe, significant geologic information can be extracted from this property to better understand provenance (source of material) and environmental conditions. Various shape parameters are used to classify rocks in terrestrial studies, including elongation (or aspect ratio), ruggedness (or angularity), and surface area. In OASIS, an ellipse is fit to the outline of the rock. The eccentricity of the fit ellipse as well as the error is computed. The angularity of each rock is assessed using a measure of ruggedness. Further, another shape parameter identified is the orientation of the rock with respect to the ground.

Target Signature Prioritization

Once rocks and their properties are identified in images, OASIS contains several methods to prioritize these identified features. One method for prioritization, which will be used for automated targeting on MER, is called *target signature*. This algorithm enables scientists to efficiently and easily stipulate the value and importance to give each particular feature. Terrain targets are then prioritized as a function of the distance of their extracted feature vector from the specified weighted feature vector. Scientists can either manually specify a feature vector, or they may select a rock (or other target) from among the set of terrain targets already identified and have the targets ranked as a function of the distance of their feature vectors from the feature vector of the selected target. Figure 3 shows an example of using target signature with the FIDO rover to look for rocks of high albedo in the JPL Mars Yard.

Figure 3 - Image taken by JPL FIDO rover (in JPL Mars Yard) when searching for rocks of "high albedo" (or light-colored).

4. SCHEDULING OPPORTUNISTIC SCIENCE

When the OASIS data analysis software identifies science targets of interest (e.g., a rock with certain characteristics), a science alert is generated. This results in a new science goal being passed to the planning and scheduling module which determines if the new measurement request can be accommodated. If it can be, the current rover command sequence is modified to collect new science data.

The OASIS planning and execution module [4] is intended to run with little communication with ground. It accepts new science goals and then modifies the current rover command sequence (or plan) to try and achieve as many of the goals as possible while still respecting relevant state and resource constraints. This module also executes the current rover plan by dispatching commands to the rover's low-level control software and monitoring relevant state and resource information to identify potential problems or opportunities. If problems or new opportunities are detected, the system is designed to handle such situations by using re-planning techniques to add, move, or delete plan activities

Planning capabilities for OASIS are provided by the CASPER continuous planning system [5]. Based on an input set of science goals and the rover's current state, CASPER generates a sequence of activities that satisfies the goals while obeying relevant resource, state and temporal constraints, as well as operation (or flight) rules. Plans are produced using an iterative repair algorithm that classifies plan conflicts and resolves them individually by performing one or more plan modifications. CASPER also monitors current rover state and the execution status of plan activities. As this information is acquired, CASPER updates future-plan projections. Based on this new information, new conflicts and/or opportunities may arise, requiring the planner to re-plan in order to accommodate the unexpected events.

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[2] Shadows and sun angle can both affect the gray-scale value of a pixel. Although this can be corrected by using the range data along with knowledge of both the sun angle and the camera orientation, the current system does not address these specific issues.

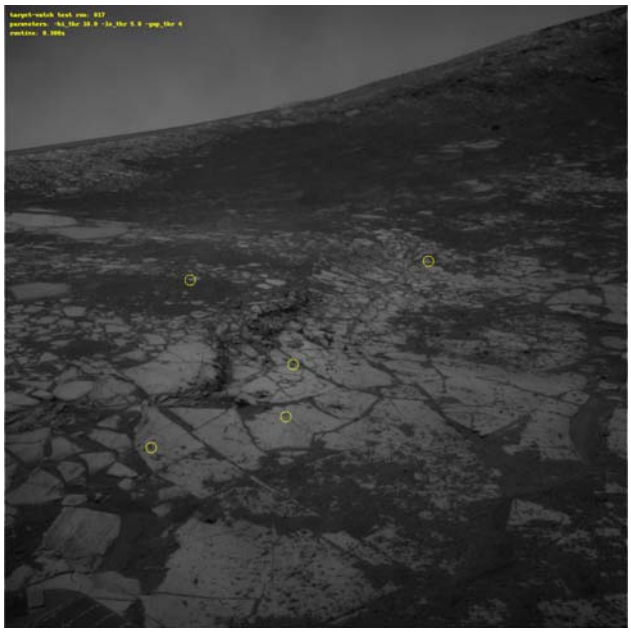

Figure 4 - OASIS selects five potential targets for a limited FOV instrument, such as the 2009 MSL ChemCam, to sample. This image was taken on the MER mission by the MER navigation cameras. Autonomously selecting targets vs. blind sampling greatly increase the chances of accurately targeting a rock.

To handle opportunistic science, we enabled the OASIS planning and execution module to recognize and respond to science alerts, which are new science opportunities detected by onboard data-analysis software. For example, if a rock is detected in navigation imagery that has a previously unseen shape or texture, a science alert may be generated to take additional measurements of that rock.

5. AUTONOMOUS TARGET SELECTION AND SAMPLING

One important application of the OASIS system is to provide autonomous targeting for science measurements that cannot be easily selected in advance. As mentioned earlier, the automated targeting element of OASIS has been named AEGIS and will soon be used onboard the MER rovers. A number of rover remote sensing instruments have a very narrow field-of-view and thus require selection of specific focused targets for sampling. Such instruments include the MER Mini-TES spectrometer, the MSL ChemCam spectrometer, infrared point spectrometers as was as Panoramic cameras (especially when taking subframed images). Targeting these instruments by mission personnel on Earth currently requires a lengthy process. The typical scenario for selecting targets is to manually identify the targets using data that has already downloaded on a previous sol. Thus after reaching an end-of-day location, the rover must sit and wait until images can be analyzed and new measurement commands can be uplinked (which at best will happen on the next sol).

By analyzing image data onboard, AEGIS can autonomously select targets for these instruments and execute a set of measurement activities that do not exceed current rover resources. These techniques could be used, for example, on the MSL mission to select targets for the ChemCam instrument to sample at the end of a long rover drive.

To select potential targets, an image panorama of the surrounding area is taken, and then using an OASIS target detection algorithm, rocks and other targets in the scene are autonomously identified. Next, a subset of those targets are selected and prioritized based on scientist-selected criteria using the OASIS target signature algorithm. For instance, the target signature could be based on terrain target shape, albedo or size. Once a subset of target rocks is identified, points on these rocks are selected as specific instrument targets. Figure 4 shows the five potential rock targets selected in a MER navigation camera image where rock size was used for prioritization of target. Note as mentioned previously, the OASIS target finder is run in mode that decreases the number of false positives (e.g., finding a shadowed area of sand vs. a rock) but overall finds fewer of the overall rocks in the image. A small study of target selection in MER panoramas showed that using OASIS provided a 68% chance of accurately targeting a rock vs. a 9% chance if a pixel is selected randomly [6].

Since only a limited amount of time or resources may be available to take these measurements, the OASIS planning and scheduling subsystem is used to only schedule measurements that can be safely executed based on the rover health and current state. Currently, an iterative optimization approach is used to schedule additional science measurements within the rover's current command sequence. In this approach, science measurements that have been selected by onboard data analysis are added to the plan and the planner attempts to accommodate each measurement. If not all additional measurements can be added due to resource or other constraints, the planner iteratively deletes the lower priority measurements first. Typical constraints include a limited time window within to add end-of-day measurements, a limited amount of rover energy for that sol (which may have fluctuated from predicted levels due to activities earlier in the day), and a limited amount of onboard memory to store science data.

To test AEGIS on this application, we did a large amount of testing with the FIDO rover in the JPL Mars Yard (shown in Figure 5). For testing, we had the rover drive to an end-of-day location, where it would then take a full (or partial) panorama with the rover navigation cameras. Images were then analyzed by AEGIS for target identification and property analysis. For this testing, our target signature was

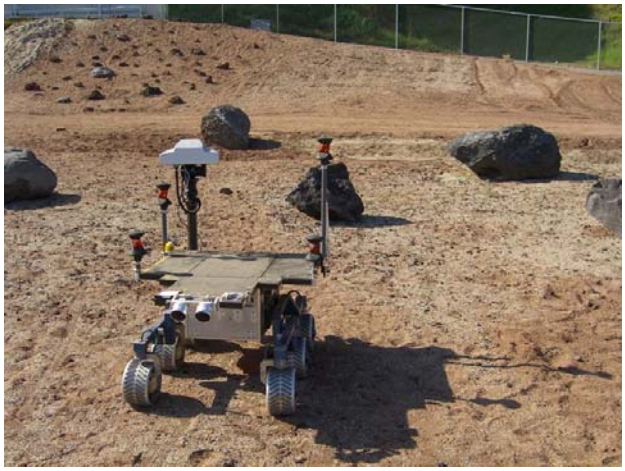

Figure 5 - FIDO rover in JPL Mars Yard

to prefer larger rocks for targeting, where this specification was suggested by the MSL ChemCam PI. Measurements requests for a subset of identified rocks were then sent to the planning subsystem; measurements were also prioritized based on estimated rock size, where larger rocks had the highest priority.

Once it receives the new measurement requests, the planner attempts to schedule as many new measurements as possible given rover constraints. New measurements are executed with the FIDO panoramic cameras, which provided an example limited FOV instrument that could take measurements of very specific target areas. Figure 6 shows an example of a large rock identified in a navigation camera image and the resulting panoramic camera image. This scenario was run successfully with FIDO using various rock configurations and onboard resource levels.

6. AUTOMATED TARGETING ON MER ROVERS

Currently, the AEGIS automated targeting capability is being prepared for upload to the MER rovers in early 2009. Specifically, AEGIS will provide technology for *targeted* remote sensing of the MER Panoramic Cameras[3] (for high resolution, 13 filter, subframed images) in an automated fashion during or after rover traverses. Currently on MER only untargeted remote sensing is possible immediately after or during a traverse, where typically wider field of view instruments are used such as the MER navigation cameras or the MER Panoramic cameras in a full-frame lower-resolution (single filter) mode.

6

[3] The MER Mini-TES spectrometer is another example of a limited FOV instrument where the AEIS automated targeting technology would be very beneficial. Unfortunately, since the MER rovers have been in operation for over five years, the Mini-TES instrument on the Opportunity rover is no longer functional and the Mini-TES instrument on Spirit is expected to lose functionality in the near future. Thus OASIS automated targeting technology will not be demonstrated on this instrument.

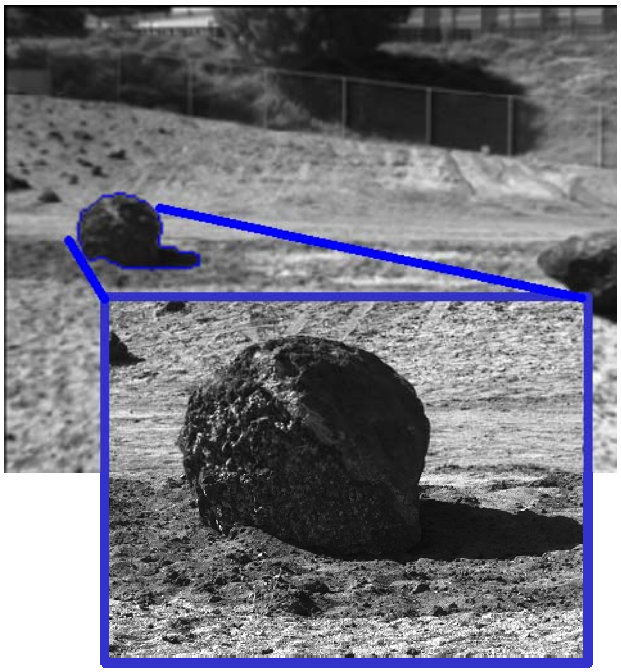

Figure 6 - An example of a large rock autonomously selected and targeted by a limited FOV instrument on the FIDO rover. In this case, a large rock was identified in a FIDO navigation panorama and then targeted with the FIDO high resolution panoramic camera. (Both cameras on FIDO provide grayscale images.)

AEGIS will enable the rover flight software to analyze imagery onboard in order to autonomously select and sequence targeted remote-sensing observations in an opportunistic fashion. This capability is especially useful for multi-sol plans where a drive is performed on the first sol. Currently only untargeted remote sensing can be done on the second and third sols since ground does not have imagery of the rover's new location. Using AEGIS, targeted remote sensing can be performed on these sols, significantly increasing science gain for multi-sol plans. Further, targeted measurements could also be made during or after a long traverse. Figure 7 illustrates the additional targeted measurements that could be acquired during or after rover drive activities.

Onboard MER trials will be performed to demonstrate and validate the AEGIS capability. When this capability is run, AEGIS will perform the following tasks onboard:

1) **Point and capture a navigation camera image.** Pointing parameters will be selected by the ground scientists and engineers as part of the sequencing process.

2) **Analyze navigation camera image for targets and characterize those targets.** The afore-mentioned target finder (from Section 3) will be

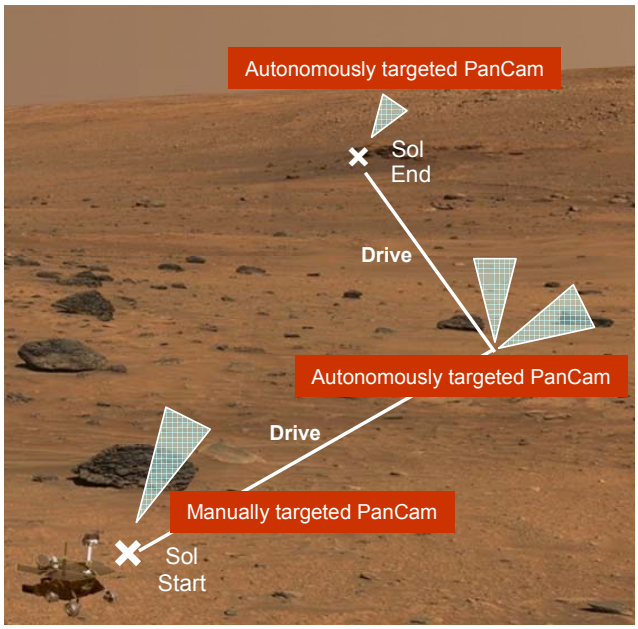

Figure 7 - New MER capability for automated targeting. The AEGIS software will enable MER to analyze images onboard to autonomously select and sequence targeted remote-sensing observations using the limited FOV panoramic cameras.

used. Target properties that will be calculated include albedo, size and shape properties.

3) **Select the top target candidate** using the AEGIS target signature algorithm and a target feature set provided by scientists. For instance, scientists could specify that targets rocks have a large size, round shape and light albedo.

4) **Determine 3D pointing requirements of top target**. An enscribed circle method is used to select a center point on the target at which a limited FOV instrument can pointed.

5) **Point panoramic camera at top target** using determined pointing requirements.

6) **Acquire a sub-framed high-resolution 13 filter panoramic camera image of top target** and download with other standard data products.

Science targets will include rocks and other terrain features that match pre-set scientist criteria that will be determined during sequencing. The AEGIS automated targeting capability will be scheduled and run using a process similar to the one in place for the onboard dust-devil and cloud detectors [2]. Parameters can be set during sequencing to specify navigation camera pointing and science-target features to prioritize highly, such as rock albedo or size.

The resulting Panoramic Camera images will be downlinked with other standard MER data products. New images will also be relatively inexpensive to downlink since only subframed images will be taken. This result will show how a mission can receive high-quality opportunistic data without requiring a large amount of resources, such as downlink bandwidth, or onboard storage

There are several significant differences in how the AEGIS automated targeting capability is being applied on MER vs. how it was used when testing with the JPL FIDO rover. One difference is that the AEGIS automated planning and scheduling capability will not be used to schedule the opportunistic response image. Instead, the ground sequencing team will assume that a high resolution sub-framed panoramic camera image will always be taken when this capability is run and will allocate the necessary time and resources during ground planning. This change in operation was made for several reasons including very limited computing resources being available onboard the vehicles and a desire to keep the complexity and cost of the new technology as reduced as possible. In future iterations of this and other AEGIS capabilities, we do plan to include automated planning as a key technology supporting autonomous science.

Another difference is the interface which the AEGIS will use to point the MER panoramic camera. To enable pointing of this instrument on MER, OASIS will use pointing commands available through the Visual Target Tracking Capability [7], which has a direct interface to point the MER navigation camera that can also be used to point the MER panoramic camera. This setup is due to the fact the automated targeting technology is being added to the MER mobility module (which is also where other new capabilities have been added, such as MER 9.3 technologies [8]). This module contains no direct interface to point the MER panoramic camera, thus AEGIS will use a VTT command to achieve the desired panoramic camera pointing. Finally, one last difference is that stereo information for the initial navigation camera image could not easily be made available to AEGIS onboard the rovers. Thus the size property for identified target is calculated using pixel size vs. size determined through stereo information. Though pixel size is less accurate it has in general produced good result in tests.

7. SUMMARY

This paper provides an overview of the AEGIS automated targeting capability. This capability has been evaluated on the JPL FIDO rover and is now being prepared for upload to the MER mission rovers in early 2009. The AEGIS automated targeting system will enable targets of scientific interest to be automatically recognized in MER navigation camera imagery. These targets can then be successfully sampled using limited FOV remote-sensing instruments, such as the MER Panoramic Camera or the MSL ChemCam

spectrometer without requiring a communication cycle with ground operators. Instead, new measurements can be acquired during or immediately after a long drive, and before images of the rover's current location have been acquired and analyzed by ground.

8. ACKNOWLEDGMENTS

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