Automated Targeting for the MSL Rover ChemCam Spectrometer

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Abstract

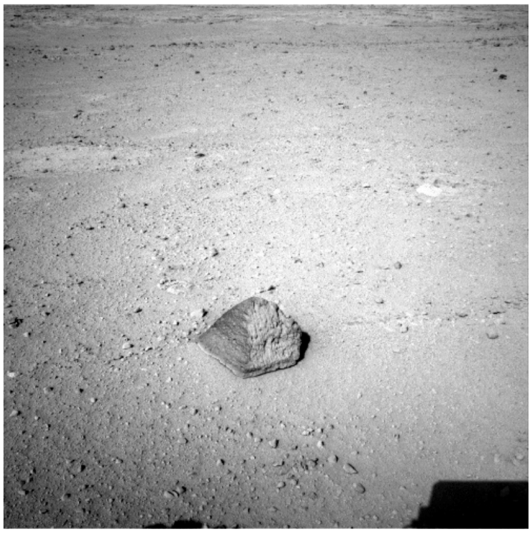
The Autonomous Exploration for Gathering Increased Science (AEGIS) system enables automated science data collection by a planetary rover. AEGIS analyzes rover images onboard to detect pre-defined science features of interest, enabling targeted instrument data to be acquired immediately with no delays for ground communication. AEGIS analyses images to detect candidate targets and then selects specific features for followup measurements based on scientist-specified objectives. This paper describes the application of AEGIS for use with the Mars Science Laboratory (MSL) mission ChemCam spectrometer. ChemCam uses a Laser Induced Breakdown Spectrometer (LIBS) to analyze the elemental composition of rocks and soil. AEGIS applies to ChemCam in two ways. The first involves automated targeting of ChemCam during or after long drives by finding rock targets in Navigation Camera images. The second involves refining ChemCam pointing by detecting small targets, such as veins or concretions, in Remote Micro Imager images. This paper describes both of these applications.

1 Introduction

The Autonomous Exploration for Gathering Increased Science (AEGIS) system provides automated, science-driven data collection for planetary rovers. The AEGIS software has been in use on the Mars Exploration Rover (MER) mission Opportunity rover since 2010 to provide intelligent science targeting capabilities for remote sensing instruments [1]. AEGIS enables targeted data to be rapidly acquired from scientifically interesting targets with no required ground communication and at times otherwise not possible with traditional methods, such as during or immediately after long drives. Geological targets for rover remote-sensing instruments, especially narrow field-of-view instruments, have traditionally been selected manually based on imagery that has already been transmitted back to the operations team on Earth. Through the use of data analysis techniques, AEGIS analyses imagery onboard to autonomously select high priority science targets, typically rocks based on criteria provided by scientists (e.g., rock size, shape, intensity). When high priority targets are identified, AEGIS can automatically acquire new data on those targets without requiring communication with the ground operations team. AEGIS has been used on the Opportunity rover to automatically acquire high resolution, 13-filter color images of rock targets using the MER Panoramic cameras.

AEGIS is now being applied for use with the Mars Science Laboratory (MSL) mission ChemCam spectrometer. The MSL Mission Curiosity Rover successfully landed in 2012 and is currently in the first year of its prime mission. Its major goals are to study Mars habitability, climate and geology. One of the key remote sensing instruments on Curiosity is the ChemCam Laser Inducted Breakdown Spectrometer. ChemCam uses a Laser Induced Breakdown (LIBS) Spectrometer, which can analyze the elemental composition of rocks and soil from up to seven meters away [2]. ChemCam’s tightly-focused laser beam (350-550 um) enables targeting of both large and very fine-scale terrain features. Figure 1 shows examples of two different rock targets sampled by ChemCam.

AEGIS is being applied to the ChemCam instrument in two ways. The first application is to enable automated targeting of ChemCam on rock targets that are visible in Navigation Camera imagery where data would be collected during or after long drives. The majority of ChemCam measurement targets are selected manually using prior imagery. However this requires the rover to



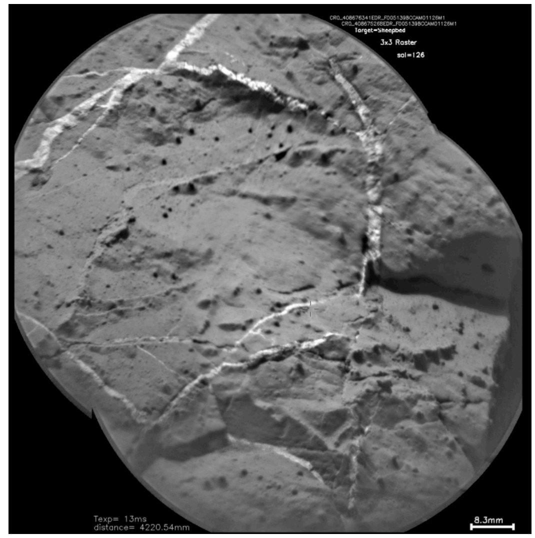


Figure 1. Examples of rock targets sampled by the MSL ChemCam instrument, which is capable of sampling a range of rock sizes from large rocks to very fine scale terrain features. The image on the left shows a 50 centimeter wide rock (Jake Matijevic) in a MSL Navigation Camera image that was sampled by ChemCam on sol (or Martian solar day) 48. The image on the right shows a set of small veins (some smaller than 1 millimeter in width) in a Remote Micro Imager (RMI) image that were sampled by ChemCam on sol 126 (Sheepbed target).

stay in the same area while images are downlinked, analyzed for targets, and new commands uplinked. More rapid collection requires blind targeting, where measurements are often of soil patches instead of more valuable targets such as rocks with specific properties. AEGIS is being applied to automatically analyze images onboard and select targets for ChemCam analysis. This approach allows the rover to autonomously select and sequence targeted measurements in an opportunistic fashion at different points along the rover's drive path. Rock targets can be prioritized for measurement based on various geologically relevant properties, including size, shape and intensity.

A second application is to enable intelligent pointing refinement of ChemCam when acquiring data on small targets, such as veins or concretions that are only a few millimeters wide. These targets have high science value and are typically hand-selected by operators on the ground. However, due to backlash and other pointing challenges, hitting these small targets often requires several downlink cycles. Often targets must first be imaged using the high resolution ChemCam Remote Micro Imager (RMI) and then ground analysis performed to enable a fine-tuned pointing correction on the next commanding cycle. AEGIS is being applied to analyze RMI images onboard and automatically determine the pointing refinement in a single command cycle. This significantly decreases the amount of time and resources required to acquire ChemCam data on such targets. Since Curiosity is in the middle of an eight kilometer long drive to Mount Sharp, only very limited stops can be performed to collect science data. Thus the capability for automated or rapid science data collection will be quite beneficial.

2 AEGIS System Overview

As previously mentioned, the AEGIS system enables autonomous operation of science instruments that target specific terrain features, such as rocks with certain physical properties. AEGIS focuses on using onboard data analysis to acquire new instrument data on science targets that have been identified in an opportunistic fashion. To date, a number of rover remote-sensing instruments have used relatively narrow fields-of-view (FOV, e.g., < few degrees) optics and thus require selection of specific focused targets for data collection. For use on the Curiosity rover, the AEGIS system was extended to identify additional types of targets (such as small veins) and to select targets that could be sampled with the ChemCam spectrometer.

For MSL, AEGIS involves six steps that are shown

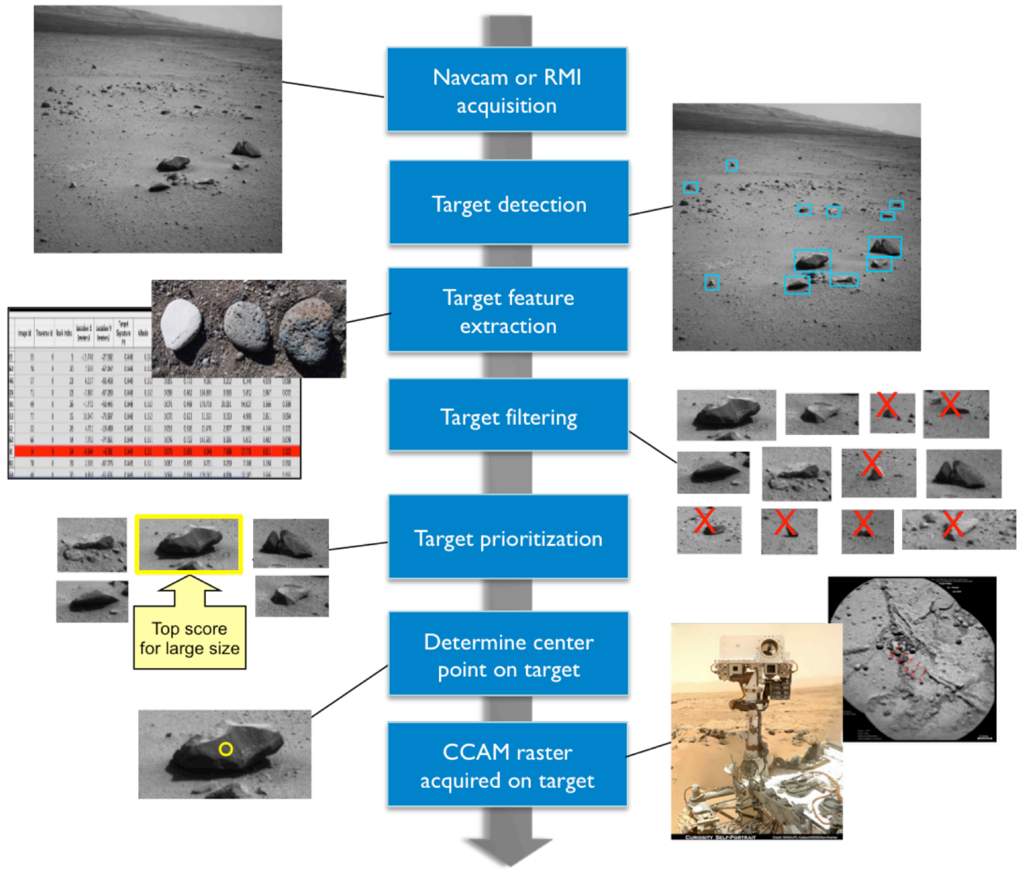


Figure 2. AEGIS Process Steps. When AEGIS is sequenced, the above series of steps will be executed onboard the MSL Curiosity rover. Parameters can be set during sequencing to specify camera pointing, feature values to use for target filtering, and feature values to use for target prioritization (e.g., prioritize by rocks of large size and high intensity).

in Figure 2 and described below:

- **Acquire an image with the MSL navigation camera or the RMI camera:** Scientists and other sequence team members select image parameters, such as the pointing direction and resolution, during the AEGIS sequencing process. If selecting targets from a Navigation camera image, the camera is typically pointed at a terrain area where potential science targets may be in view. If selecting targets from an RMI, with its 1° FOV, scientists have already chosen a promising target area and are relying on AEGIS to detect very small targets (e.g., ~ 1 mrad or less) in the RMI FOV.
- **Analyze the Navigation camera image or RMI image for potential terrain targets:** AEGIS uses two different approaches to identify targets. One algorithm, called Rockster, looks for enclosed boundary contours (defined by intensity edges) in grayscale imagery. Another method, called TextureCam, uses a machine learning approach to classify surfaces in the image based on their visual appearance. Targets in Navigation camera images typically correspond to rocks. Targets in RMI images typically correspond to veins, nodules, concretions or other small features.
- **Extract relevant target features:** AEGIS calculates a set of target features (or properties) for each candidate target. These properties include measures of size, intensity, shape, orientation, and rock location.
- **Filter targets:** This component filters out targets that don't match certain criteria. For example, AEGIS will typically be setup to only consider targets that are seven meters or less from the rover, since that is the typical range limit on ChemCam

LIBS measurements.

- **Prioritize targets:** This component uses a prioritization algorithm to analyze target property data and determine a set or ranked target candidates. Scientists provide a "target signature" in the command sequence. This defines a figure of merit using a linear combination of one or more target properties. Example signatures are "high intensity", "round shape", "large targets with high eccentricity", etc.
- **Acquire new data:** AEGIS acquires new data with the MSL ChemCam instrument on the top N targets where the specifics of the response are decided by the operations team during sequencing. It is expected that a LIBS raster sequence will typically be acquired on the top three to five targets.

The next few sections give more detailed information on each of these steps.

3 Terrain Target Detection

AEGIS contains two methods for terrain target detection. The first method uses the Rockster algorithm, which was also used on the MER rovers, to detect enclosed edges in grayscale imagery. The second method uses a machine learning method to classify surfaces based on their visual appearance. This method will be included in the upload if flight environment constraints on space and memory allow. Both methods are explained below.

3.1 Rockster

AEGIS uses the Rockster algorithm to identify a set of targets in the navigation or RMI camera image. Rockster identifies edge segments in grayscale imagery and searches for objects with an enclosed boundary. Such objects typically correspond to rocks when looking at the Mars terrain but could also correspond to small craters or other terrain features. Rockster initially locates partial boundary contours of targets using a procedure similar to the Canny edge detector. Specifically, Rockster calculates the intensity gradient 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.

A gap-filling mechanism joins nearby contour fragments whose endpoints lie within a predefined radius. The final step is to regroup the edge fragments into coherent contours, which is accomplished through background flooding. Figure 3 shows a high-level view of the process that Rockster uses to detect and generate usable target contours.

For automated targeting of limited FOV instruments, false detections are costly and high precision is important. Thus for this application, Rockster is typically run in a mode that reduces false positives; however, this also has the effect that fewer overall targets are found. This behavior is a trade-off that can be adjusted depending on the application, i.e., for some applications it may be more important to find a larger percentage of the true targets despite the higher risk of returning some false positives (i.e., non-interesting targets). The sequencing team can also choose to limit target detection to specific rectangular sub-regions of the image.

Due to the limited processing capacity and memory available onboard the MER and MSL rovers, Rockster relies on techniques that can perform quickly and robustly in such an environment. Image preprocessing, in particular, smoothing reduces the total number of edge elements detected. Considering fewer edges saves considerable computational effort in downstream gap-filling and contour following. Rockster also tracks a number of internal space and time complexity measures related to the overall segmentation computation.

3.2 TextureCam

A second method of rock detection uses a machine learning-based pixel classifier called TextureCam [3]. This approach uses image texture to differentiate and map geologic surfaces. Here the term "texture" is used not in the geologic sense of formal physical properties, but rather in the computer vision sense to signify statistical patterns of image pixels. These numerical signatures can automatically distinguish geologically relevant elements such as dust or sand, surface roughness, formulate texture analysis is as supervised classification of each image pixel from training examples. The workflow includes ground and onboard components. On the ground, designers label a training set of image pixels according to geologic surface type, and train a statistical model that relates the local statistics of each pixel to its class. A machine learning approach is adopted, where labeled images are used to train a random forest classifier. The model relates diagnostic patterns of

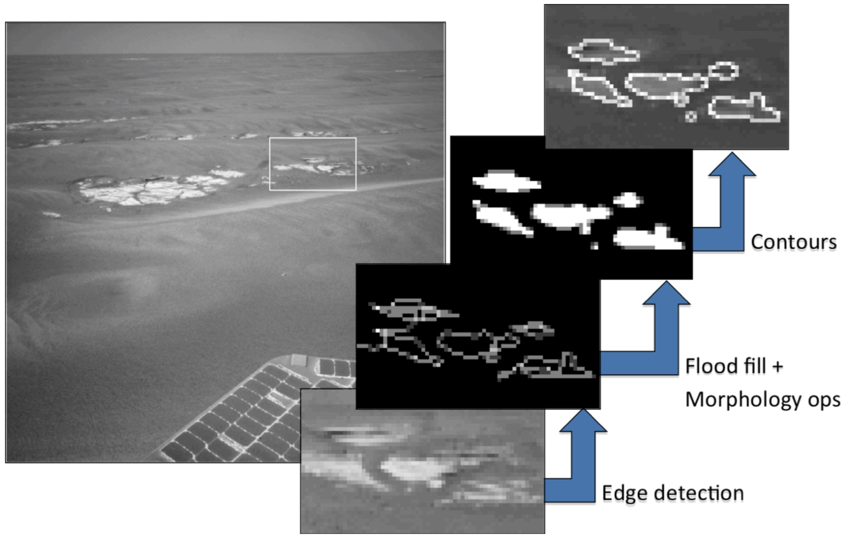


Figure 3. AEGIS Target Detection using Rockster. This picture shows the major steps performed when AEGIS analyzes an image for rock targets. The goal of target detection is to search for objects in the image that have an enclosed boundary. Target detection can be performed in Navigation camera images (as shown in this example) or in RMI images.

bright and dark pixels to a pixel's class. It ascribes a probabilistic surface classification to each pixel based on any available input data, including 3D stereo data, monochrome, or multi-channel images. The resulting classification model can be represented in a few tens of kilobytes and uploaded to the rover as part of the AEGIS system. The second stage operates in real time onboard the vehicle. Here, the carefully trained model can generalize to predict pixel classes for new scenes under different terrain and lighting conditions. Figure 4 shows an example classification identifying veins in an RMI image.

4 Target Feature Extraction

Once candidate targets are identified, the AEGIS system computes numerical attributes corresponding to properties of each target image region.

4.1 Intensity

The pixel intensity of a target is an indicator of the integrated reflectance properties of a target's surface. The reflectance properties of a rock can provide important information about its mineralogical composition. AEGIS measures intensity by computing the mean gray-scale value of the pixels within the target. Note that this value can be affected by shadowing or sun angle so the calculation does not provide a perfect measure of physical surface albedo. However, it provides some useful information about surface properties. It has proved useful for discriminating between shaded rocks protruding above the sediment, and flat rock outcrop that generally appears brighter to the sensor. AEGIS also calculates variance of the pixel intensity distribution, which can serve as a rough proxy for texture.

4.2 Size

One of the most important properties of rocks on the surface is their size, which can be used to identify sorting and geologic contacts. Several features are used in AEGIS to describe the target size. The pixel area of the rock is one simple measure. AEGIS also calculates the radius of the largest inscribed circle that fits within the contour. It computes this latter measure efficiently using an image distance transform. A third measure of size is the length of the semi-major and semi-minor axes of the best-fitting ellipse. AEGIS fits an ellipse to the rock's outline using a least-squares criterion. A final measure of size uses stereo data to estimate true target size.

4.3 Location

Different factors regarding target location are computed, which allows the operators to favor or exclude candidates based on their position in the surrounding terrain. These features include the distance to the target, the absolute azimuth and elevation values for pointing at the target center, and the site x, y and z of the target center.

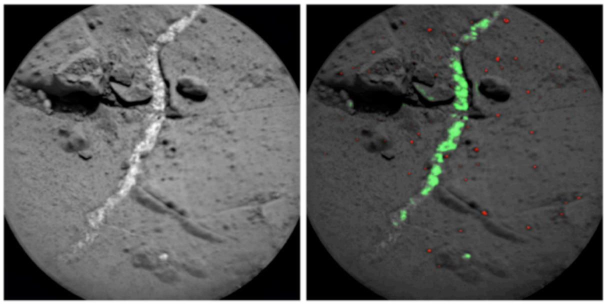


Figure 4. AEGIS Target Detection using TextureCam. This picture shows an example classification result for identifying veins in an RMI image (target Tukarak, image FOV = 5 cm @ 2.4 m).

4.4 Shape

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. AEGIS uses the eccentricity of the fit ellipse as well as a ruggedness score based on the square of the perimeter divided by the contour's pixel area.

5 Target Prioritization and Filtering

Scientists can specify multiple filters that remove from consideration any target where the value of a specified feature falls outside a threshold (either above or below). This is useful for excluding targets that are likely spurious detections, such as very small rocks or for excluding objects too far away from the rover for LIBS data acquisition, which is typically performed within seven meters of the vehicle. The sequencing team sets all feature selection and filter parameters manually and can change them each time AEGIS is used. In addition to feature-based filtering, AEGIS also removes all targets with contours that intersect the known locations of the rover body.

AEGIS next prioritizes candidate targets and calculates a candidate ranking. To guide the prioritization process, AEGIS uses a pre-specified target signature, corresponding to particular feature attributes (e.g. prefer rocks that are large in size and have a high intensity), provided by the MSL science team during ground sequencing. This algorithm enables scientists to efficiently and easily stipulate the importance of each particular feature. For each run of AEGIS, scientists can use multiple target signatures to rank target candidates. These signatures can also be changed each time the system is run. For each target signature, AEGIS gives each candidate target a score f corresponding to a weighted sum of an arbitrary number of feature values x_i. A coefficients, α_1, controls whether the algorithm prefers high or low feature values, while a weighting coefficient β_i describes the comparative importance of the feature.

$$f = \beta_1\alpha_1x_1 + \beta_2\alpha_2x_2 + \ldots \beta_n\alpha_nx_n,$$
$$\alpha_i \in \{-1,1\},\ \beta \in [0,1]$$

Note that users can also specify only one feature to rank upon if desired.

6 New Data Acquisition

When sequencing AEGIS, the ground team decides how many top targets will be sampled using the ChemCam instrument A common procedure will be to acquire 2D rasters of ChemCam LIBS measurements on the top three to five targets. Figure 5 shows the top five targets found in an MSL navigation camera image and a RMI image. On the left, AEGIS was directed to prioritize targets of large size. On the right, AEGIS was directed to prioritize targets of large size and high intensity. LIBS rasters will be centered on each target by determining the center point of the largest inscribed circle that fits within target contours. A sample 3x3 LIBS raster is shown in Figure 6.

7 MSL Integration Status

AEGIS is planned for upload in late summer 2014. Currently AEGIS is being integrated with the MSL flight software and validated on MSL testbeds, including the MSL Vehicle System Testbed (VSTB), which is a close double to the Curiosity vehicle on Mars.

AEGIS will be run as part of the MSL onboard flight software, which imposes strict computational and resource constraints. All AEGIS components will run onboard the MSL 133 MHz RAD750 flight processor, with 256 MB of DRAM, 128 MB of RAM, and 4 GB of flash memory. Even though it processes full-frame images of over 1 MB each, AEGIS is required to run using less than 16 MB of total RAM to ensure other onboard processes are not impacted. Time efficiency is also important. Though the RAD750 is significantly

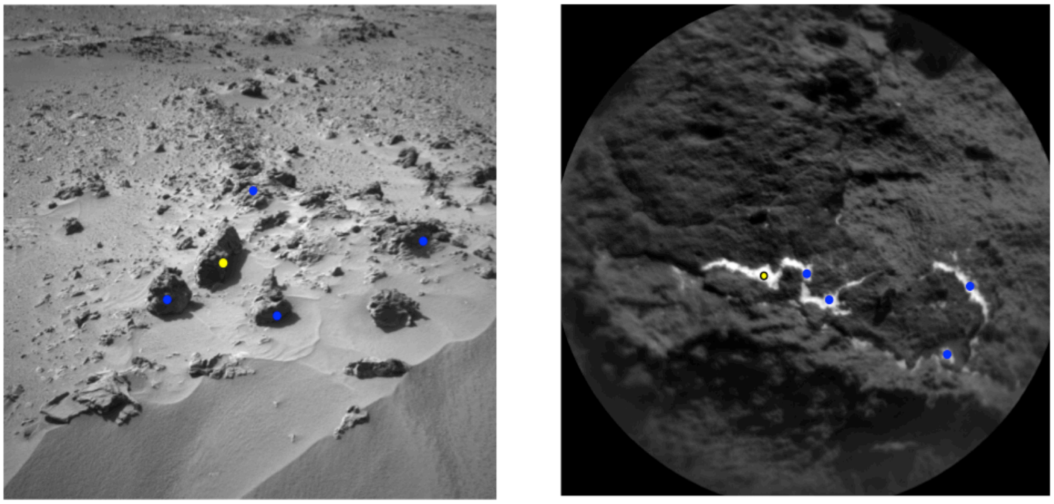


Figure 5. Sample AEGIS target prioritization in MSL images. On the left, AEGIS was directed to select the top five targets based on rock size in an MSL navigation camera image. On the right, AEGIS was directed to select the top five targets based on a combination of rock size and high intensity in a MSL RMI image (Mell target, FOV = 15 cm).

faster than the MER RAD6000, it is still several orders of magnitude slower than a modern commercial processor. Thus operations requiring a fraction of a second on a modern processor could easily take seconds to minutes on the MSL flight processor. AEGIS target selection is predicted to require several minutes of runtime. (On a quad-core 3.0 GHz Intel Core 2 with 8 GB of memory, AEGIS requires less than 1 second to process a typical image.)

8 Related Work

AEGIS builds on a foundation of related work in autonomous rover science systems. Terrestrial platforms have demonstrated classification of terrain types or features in analog planetary surface environments, as well as automatic followup utilizing cameras and spectrometers. One early system autonomously identified meteorites in Antarctica [4]. Another system provided techniques for analyzing field test data by the Marsokhod rover [5]. Other research focused on the problems of feature extraction [6].

Some experiments have focused on autonomous science during longer traverses, such as field campaigns to characterize the distribution of life in the Atacama Desert [7] and the geology of Amboy Crater [8]. Researchers have also investigated automated target selection for the ESA ExoMars rover mission [9,10]. More recently work has been done using edge detection techniques to recognize stromatolite layering [11] and using Cartesian genetic programming to perform terrain classification [12].

A separate image processing approach has been used on the MER rovers to detect dynamic atmospheric phenomena, such as dust-devils, in rover images [13]. However, this approach to event detection is quite different than the AEGIS analysis and looks for differences between a series of images to detect areas where motion has occurred between images.

AEGIS contributes the only deployment of autonomous rover geology to planetary rover missions. This system provides an important example of how autonomous target prioritization can be used by scientists to collect data that cannot easily be realized through standard ground operations.

9 Conclusions

In summary, AEGIS enables autonomous recognition of scientifically interesting targets in MSL rover navigation camera images and ChemCam Remote Micro Imager (RMI) images. These targets can then be successfully characterized without requiring a communication cycle with mission operations on Earth. New measurements with the MSL ChemCam spectrometer can be acquired without images being downlinked to the ground or in situations where small targets are difficult to accurately measure from the

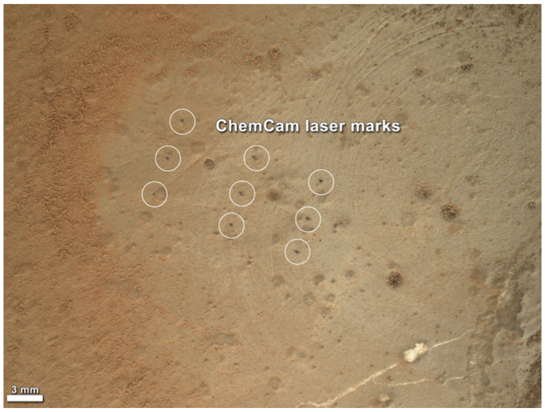


Figure 6. A MSL ChemCam 3x3 LIBS raster on rock target shown in a MSL MastCam image.

ground. AEGIS is planned for upload later in 2014. An earlier version of the system was uploaded to MER in 2010 and has successfully run multiple times on the surface of Mars.

10 Acknowledgments

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