

Developing Autonomous Science Technology for the MSL Rover Mission

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Extended Abstract

The Autonomous Exploration for Gathering Increased Science (AEGIS) system enables automated science data collection by a planetary rover. AEGIS was uploaded to the Mars Exploration Rover (MER) mission Opportunity rover in 2010 to provide onboard targeting of the MER Panoramic Camera based on scientist-specified objectives (Estlin, et al., 2012). AEGIS is now planned for upload to the Mars Science Laboratory (MSL) mission Curiosity rover to provide onboard targeting for the ChemCam instrument. ChemCam uses a Laser Induced Breakdown Spectrometer (LIBS) to analyze the elemental composition of rocks and soil (Wiens, et al., 2011). ChemCam's tightly-focused laser beam (350-550 um) enables targeting of very fine-scale terrain features. AEGIS applies to ChemCam in two ways. First, AEGIS will provide automated targeting of ChemCam during or after long drives by finding rock targets in Navigation Camera images. Second, AEGIS will refine ChemCam pointing by detecting fine-scale targets, such as veins or concretions, in Remote Micro Imager images. In this abstract, we describe both of these applications, discuss some of the challenges of integrating AEGIS with MSL flight software, and provide the current status of the AEGIS integration and upload to MSL.

For macroscopic objects, such as rocks, the majority of ChemCam measurement targets are selected manually using prior imagery. However this requires the rover to stay in the same area while images are downlinked, analyzed for targets, and new commands uplinked. It also requires

that time be taken out of the subsequent day's activity to accommodate the ground-commanded targets rather than making use of available time post-drive that could have been used if manual-targeting were not required. More rapid collection requires blind targeting, where measurements often end up being soil patches rather than more valuable targets such as rocks with specific properties. AEGIS offers the ability 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 very 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 changing thermal conditions and other pointing challenges, hitting these small targets often requires several communication 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. This correction must often be repeated several times (requiring multiple days) to ensure the target feature is hit. AEGIS will 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. In this application, the ground team selects the target and AEGIS performs an

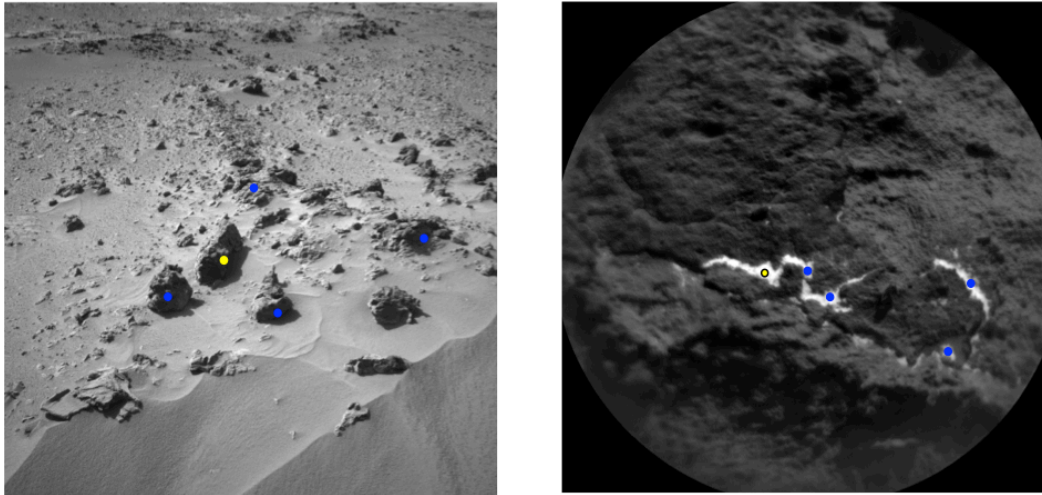


Figure 1. Sample AEGIS target prioritization in MSL images. On the left, AEGIS was directed to select the top five targets based on rock size in an MSL navigation camera image. On the right, AEGIS was directed to select the top five targets based on a combination of rock size and high intensity in a MSL RMI image (Mell target, FOV = 15 cm).

onboard analysis to determine a top set of refined targets that match the given criteria. Data on these refined targets can then be immediately collected without requiring additional communication cycles for pointing adjustment.

Both of these applications use a similar set of AEGIS capabilities, which include:

- **Identifying terrain targets:** AEGIS uses an algorithm called Rockster that looks for closed boundary contours, defined by intensity edges, in grayscale imagery. Targets in Navigation camera images typically correspond to rocks. Targets in RMI images typically correspond to veins, nodules, or concretions.
- **Extracting 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 location.
- **Filtering 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.
- **Prioritizing targets:** This component analyzes the extracted properties of each target and provides a ranking or prioritization of the top target candidates. The criteria used for ranking can be adjusted by the scientists, who provide a "target signature" as part of the AEGIS command sequence. The target signature determines the weighting of different feature properties. Example signatures are "high intensity", "round shape", "large targets with high eccentricity", etc.

Sequencing AEGIS typically involves four to eight commands, not including the commands that acquire the final ChemCam raster. Sequences for Navcam and RMI targeting are similar with only a few commands being substantially different (such as for image acquisition). When sequencing AEGIS, the ground team decides items such as image pointing, how to filter and prioritize targets, how many top targets will be sampled, and the ChemCam raster layout and sequence that will be used to perform the sampling. Targets can be re-filtered and re-prioritized as many times as desired. A common setup for sampling will be to acquire 2D rasters of ChemCam LIBS measurements on the top three targets. Figure 1 shows the top five targets found in an MSL navigation camera image and a RMI image which were used for ground testing of AEGIS. 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 through a two-step procedure. First AEGIS determines a target center point by finding the center of the largest inscribed circle that fits within target contours. Second, AEGIS uses a set of raster size parameters (set during sequencing) to calculate exactly where to start the raster so the full raster will be centered on the target.

AEGIS is planned for upload in August 2015. AEGIS is already fully integrated with MSL flight software and tested on MSL testbeds, including the MSL Vehicle System Testbed (VSTB), which is a close surrogate to the Curiosity vehicle on Mars. AEGIS was originally scheduled to be uploaded by early 2015, however, due to an anomaly with the ChemCam autofocus mechanism in November 2014,

the final AEGIS software V&V (verification and validation) and upload was delayed. A workaround for the anomaly has now been determined, which involves a change to the ChemCam instrument flight software. A recent analysis of this workaround determined that no changes to the AEGIS software were necessary. AEGIS has now begun V&V and upload should occur after that.

The AEGIS team faced a number of constraints and challenges when integrating AEGIS with the MSL flight software. One challenge with enabling AEGIS to run as part of the MSL onboard flight software was the strict enforcement of computational and resource constraints. All AEGIS components will be 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 faster than the MER Mission 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 can easily take seconds to minutes on the MSL flight processor. AEGIS target selection has required anywhere from two to seven minutes during tests on the VSTB. (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.) In addition it is important that AEGIS not disrupt other activities that must run concurrently on the CPU during AEGIS's computation.

Another challenge was ensuring that autonomous targeting of ChemCam is always safely performed. There were two important factors for addressing this challenge. The first factor was ensuring that ChemCam is never pointed at the rover body. The MSL flight software already protects against this possibility and will generate an error if that case occurs. However, AEGIS was extended to automatically rule out any targets on the rover body and ensure that such errors never occur to avoid loss of science. An articulated rover body model was incorporated into the software that enables AEGIS to rule out any targets on the rover body no matter what configuration the rover body is currently in. Note that it was not enough to simply ensure the center of a target was not on the rover body. AEGIS has to grow each target by the size of the follow-up raster to ensure that none of the rover body would ever be in view.

A second factor was ensuring that ChemCam is always kept in a "sun-safe" configuration. Allowing the instrument to point at and image the sun can cause significant damage to the ChemCam optics. To ensure AEGIS never points ChemCam at the sun, several extensions were performed both to the onboard software and the ground sequencing process. For Navcam and RMI analysis, the ground sequencing team is asked to ensure that the initial

Navcam or RMI FOV is always in a sun-safe area. To ensure that acquiring a follow-up raster on a target is always safe, where a raster may point ChemCam beyond the original image FOV, the AEGIS onboard software excludes from consideration any targets close to the image edge. Additional commands were also added that enable the ground team to set strict azimuth and elevation ranges for follow-up targets. If these commands are used, AEGIS will exclude any targets that fall outside the specified ranges.

A number of related systems have been developed to support autonomous rover science and tested on research rovers in environments such as Antarctica (Wagner, et al., 2011), Silver Lake, CA (Gulick, et al., 2001) and the Atacama Desert (D. Wettergreen, et al., 2014). Automated target selection is also being investigated for the ESA ExoMars Rover Mission (Woods, et al., 2009). However, AEGIS is the only software that has been used for autonomous geology on an actual planetary mission. It provides an important example of how autonomous target prioritization can be used in practice by scientists and integrated into standard mission operations.

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 ground. AEGIS is fully integrated with the MSL flight software and has been tested on the MSL VSTB testbed. A number of challenges were met during this integration, including enabling the software to run under strict computation constraints and extending the software to ensure safe operations of the ChemCam instrument. AEGIS is planned for upload to Curiosity in August 2015.

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