

## TWO YEARS OF AUTONOMOUS TARGETING ONBOARD THE MER OPPORTUNITY ROVER

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### ABSTRACT

The Autonomous Exploration for Gathering Increased Science (AEGIS) system provides automated, science-drive data collection for planetary rovers. AEGIS is currently being used onboard the Mars Exploration Rover (MER) mission's Opportunity rover to provide autonomous targeting of the MER Panoramic camera. Prior to AEGIS, targets were typically manually identified in images transmitted to Earth and the rover had to remain in the same location for one to several communication cycles in order to acquire new data. AEGIS analyses new images to detect pre-defined science features of interest, enabling targeted data to be acquired immediately with no delays for ground communication. Targets are selected by AEGIS through the use of onboard data analysis techniques guided by scientist-specified objectives. This paper provides an overview of how AEGIS has been used on the Opportunity rover during its 21 kilometer trek to the Mars Endeavour crater.

### 1. INTRODUCTION

The Autonomous Exploration for Gathering Increased Science (AEGIS) system provides automated, science-driven data collection for planetary rovers. The AEGIS software was uploaded to the Mars Exploration Rover (MER) mission Opportunity rover in December 2009 to provide intelligent science targeting capabilities for remote sensing instruments. 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 (such as the MER Mini-TES spectrometer and the 2011 Mars Science Laboratory (MSL) Mission ChemCam Spectrometer), 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 enables the rover flight software to analyse imagery onboard and allows the rover to autonomously select high priority science targets, typically rocks based on criteria provided by scientists (e.g., rock size, shape, reflectance). When high priority targets are identified, AEGIS can automatically acquire high quality data on

those targets without requiring communication with the ground operations team. AEGIS is currently being used on the Opportunity rover to automatically acquire 13-filter-color images of interesting rock targets using the MER Panoramic cameras. AEGIS was also awarded the 2011 NASA Software of the Year Award based on its infusion and usage on the MER Mission.

This paper will provide a brief overview of the AEGIS automated targeting capability and describe how it has been used during Opportunity's multi-year journey to the Endeavour crater. In August 2008, the MER Opportunity rover began a long distance trek to Endeavour crater (shown in Figure 1), which is a large impact crater located in the Meridiana Planum. Endeavour is 22 kilometers (or 14 miles) in diameter and is the largest crater investigated by the Opportunity rover. At Endeavour, scientists are examining older rocks and terrains for past signs of water and warmer conditions than seen earlier in the mission. After driving 21 kilometers from its August 2008 position (and 33 kilometers from its original landing site), Opportunity successfully reached Endeavour crater in August 2011.

Along the route to Endeavour, Opportunity performed many long drives. During these drives, AEGIS was used to successfully detect and capture a number of different rock types including outcrop, crater ejecta, boulders and small cobbles. A number of example results are highlighted in this paper. We also discuss related and future work. AEGIS is currently being preparing for upload to the 2011 MSL Rover Mission, which is already in flight and scheduled to land in August 2012.

### 2. AEGIS SYSTEM OVERVIEW

As previously mentioned, the AEGIS system [1] enables autonomous operation of science instruments that target specific terrain features, especially rocks with certain physical properties. To date, a number of rover remote sensing instruments have used very narrow fields-of-view (FOV) optics and thus require selection of specific focused targets for data collection. Selecting targets for these instruments has traditionally been a lengthy process requiring scientists to manually identify the interesting objects in context images obtained on a previous sol (Mars solar day) by the 45-degree FOV MER navigation cameras. Hence, at the end of a traverse, the rover could only perform "untargeted" data

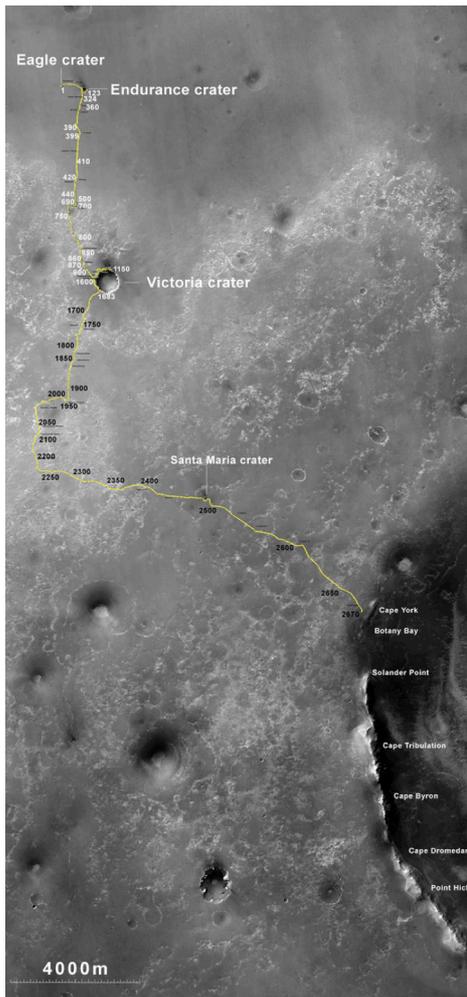


Figure 1. MER Opportunity rover traverse map showing Opportunity's path from landing to its current location at Endeavour crater. In September of 2008, the Opportunity rover left Victoria Crater to begin a long journey to Endeavour crater. In August 2011, Opportunity arrived at the rim of Endeavour after driving 21 kilometers from Victoria crater and a total of 33 kilometers for the entire mission.

collection until a new set of context images could be downlinked, analysed by the science team, and targeting instructions uplinked. This person-in-the-loop targeting requires, at a minimum, an additional sol, but in some cases could require the rover to remain at the same location for several sols. Further, due to the time required, collection of targeted data might be totally abandoned in favor of having the rover immediately proceed to a new location in response to other goals or engineering constraints.

AEGIS was designed to provide additional targeted data for the mission scientists. By analysing image data

onboard, AEGIS can autonomously select targets for onboard instruments and execute a set of measurement activities. The capabilities of AEGIS are presently being used on the MER Opportunity rover by taking additional measurements with the Panoramic camera in a high-quality (multiple color filter) mode [2].

AEGIS is run as part of the MER onboard flight software, which imposes strict computational and resource constraints. All AEGIS components run onboard the MER 20 MHz RAD6000 flight processor, with 128 MB of RAM and 256 MB flash memory. Even though it processes full-frame images of over 1 MB each, AEGIS was required to run using less than 4 MB of total RAM to ensure other onboard processes were not impacted. Time efficiency was another important limitation since operations requiring a fraction of a second on a modern commercial processor could easily take tens of minutes on the MER flight processor. The AEGIS target selection process typically runs in less than 15 minutes on the MER processor. (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.)

The AEGIS technology focuses on the task of using onboard data analysis to acquire new instrument data on science targets, typically rocks, which have been identified in an opportunistic fashion. AEGIS performs seven major steps to autonomously acquire new targeted data on an interesting science target. These steps are shown in Figure 2 and described below:

- **Acquire an image with the MER navigation camera:** Scientists and other sequence team members select image parameters, such as the pointing direction and resolution, during the AEGIS sequencing process. The navigation camera is typically pointed at a terrain area where potential science targets may be in view.
- **Analyze the navigation camera image for potential terrain targets:** Targets for AEGIS typically correspond to rocks. AEGIS uses an algorithm called ROCKSTER to look for enclosed boundary contours (defined by intensity edges) in grayscale imagery.
- **Extract relevant target features:** AEGIS calculates a set of target features (or properties) for each candidate rock. These properties include measures of size, reflectance, shape, and rock location.
- **Prioritize targets and select top target:** This component uses a prioritization algorithm to analyze rock property data and determine a top candidate. Scientists provide a "target rock signature" in the command sequence. This signature specifies what property values are of interest in the local terrain. Example signatures are "high reflectance", "round



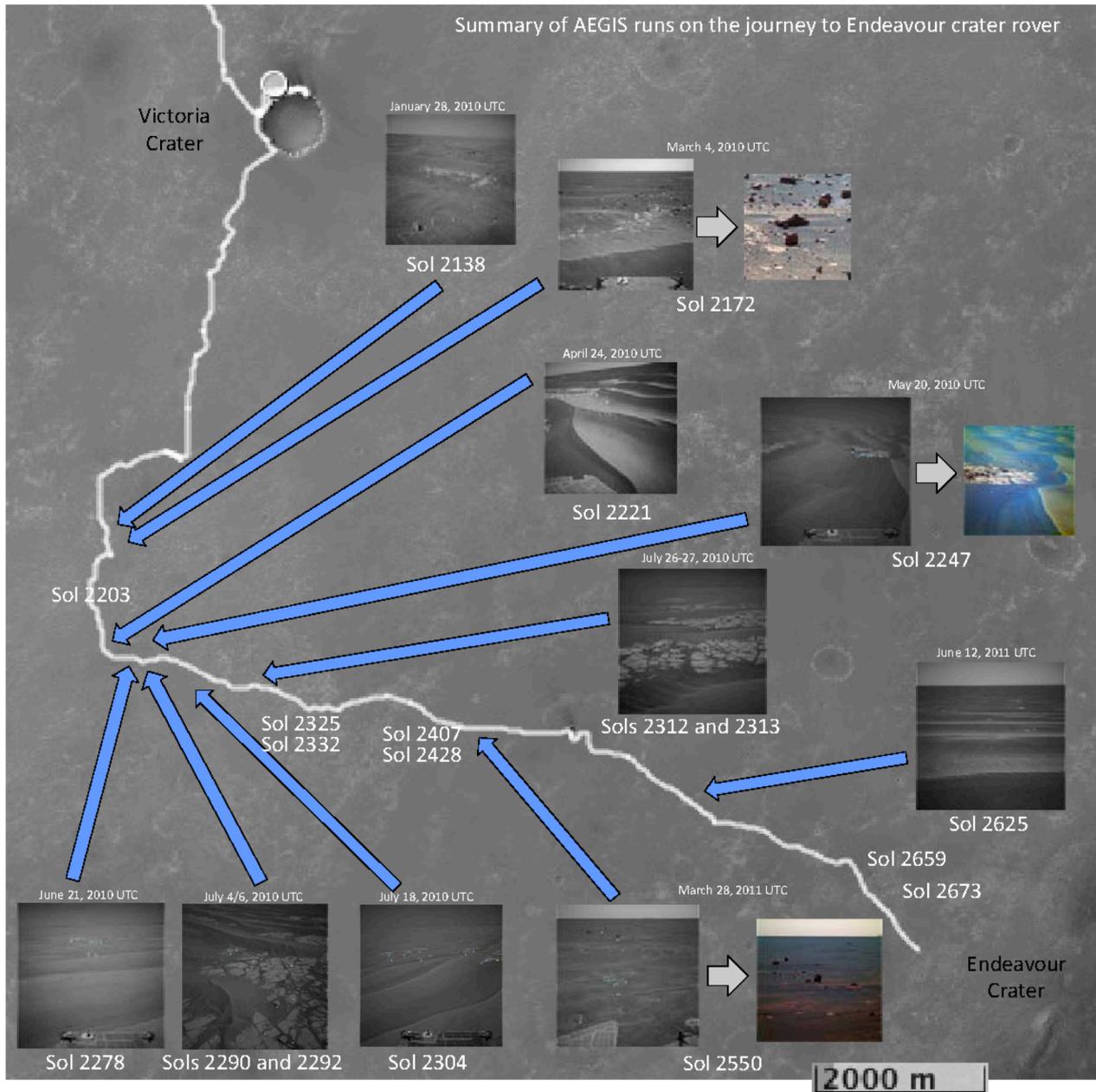


Figure 3. AEGIS usage during the Opportunity journey to Endeavour crater. AEGIS was run at a number of locations, typically at the end of long drives where AEGIS can be immediately used to collect targeted data without waiting for a communications cycle with ground operations. AEGIS was used during this time period to search for a number of different target profiles, especially using the rock size and reflectance features. Examples of targeted Panoramic camera images taken during these runs are shown in Figure 4.

signatures” were used to identify targets. Properties that were often used to prioritize targets focused on rock size and rock reflectance (which could very successfully be used to distinguish lighter colored outcrop from darker loose rock, such as cobbles and crater ejecta). On several runs, only soil was visible in the image and AEGIS correctly returned a result of no targets found. False positives have also occurred. For instance, in one

run, AEGIS was allowed to consider very small targets (less than 25 pixels), and found a set of very small false positive targets in the sand (though no rocks were in the scene). AEGIS parameters have since been modified to prevent similar occurrences.

All targeted data was acquired by AEGIS used the MER Panoramic cameras, which can acquire high-resolution

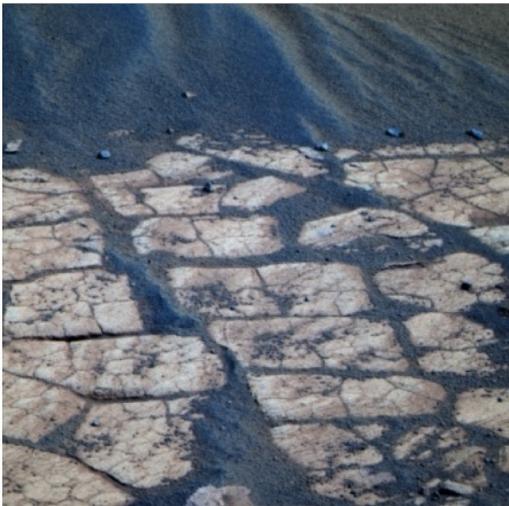
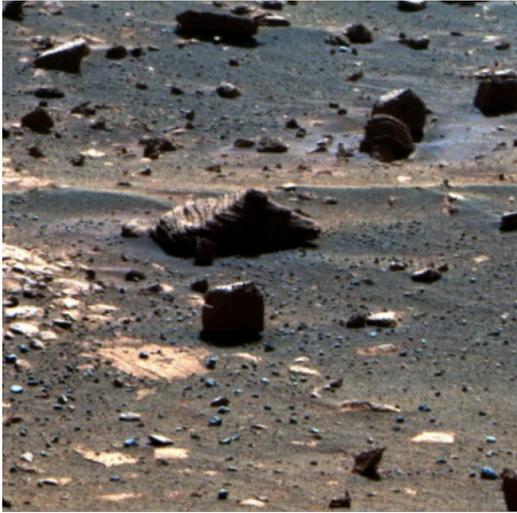


Figure 4. Examples of targeted data collected during AEGIS runs. AEGIS has been used in a variety of terrains to collect data on rock classes such as outcrop, crater ejecta and boulders. This data was collected using the MER Panoramic cameras which can collect high quality image data using 13 color filters. All data was collected autonomously by the AEGIS software during or after an Opportunity rover drive.

image data using up to 13-color filters. For these runs the Panoramic camera was run either in a full-frame mode (which covers a 16 degree FOV) or a quarter-frame mode (which covers a 4 degree FOV) [2]. The quarter-frame mode highlights how AEGIS can be used to accurately point at targets even if the pointing instrument only covers a very small area of terrain.

#### 4. FUTURE USAGE ON THE MSL MISSION

We are currently applying AEGIS for automated targeting on the Mars Science Laboratory (MSL) Rover mission, which launched in November 2011 and lands the Curiosity rover on the surface of Mars in August 2012. AEGIS will be used to collect targeted data using the MSL ChemCam spectrometer [3], which is

illustrated in Figure 5. ChemCam is a Laser Induced Breakdown Spectrometer (LIBS), which can identify elemental composition information on rocks and soil. ChemCam operates by vaporizing a small portion of rock and then collecting the light spectrum that is emitted. ChemCam can sample rocks from a distance between 1 to 7 meters from the rover and will be used to both survey rocks and identify rocks appropriate for more detailed sample analysis. We are currently working with the MSL ChemCam team to enable AEGIS to be uploaded to Curiosity and support automated targeting with the ChemCam instrument. Similar to its role on MER, AEGIS will analyse wide-angle Navigation camera images in order to determine high priority science targets that warrant ChemCam analysis. AEGIS will be used to collect single

ChemCam measurements on individual rock spots as well as measurement rasters where, for example, a 1x3 or 1x5 raster of data is collected on a small rock area. The AEGIS software will examine similar properties as detected on the MER mission, including size, reflectance and shape. We are also evaluating the use of additional rock properties that could be used in prioritizing targets on MSL or on future rover missions. For instance, one potential extension is to incorporate the evaluation of layering, texture, or color. Use of these features has and currently is being explored in other work [4,5]. For example, the TextureCam system [5] is evaluating methods for mapping terrain surfaces with texture channels that can differentiate geological properties such as roughness, pavement coatings, regolith characteristics, sedimentary fabrics and differential outcrop weathering.

## 5. 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 [6]. Another system provided techniques for analyzing field test data by the Marsokhod rover [7]. Other research focused on the problems of feature extraction [8].

Some experiments have focused on autonomous science during longer traverses, such as field campaigns to characterize the distribution of life in the Atacama Desert [9] and the geology of Amboy Crater [10]. More recently researchers have investigated automated target selection for the ESA ExoMars rover mission [11,12].

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 first deployment of autonomous rover geology to a planetary rover mission. AEGIS provides an important example of how autonomous target prioritization has been used in practice by scientists, and how the processing and follow-up has been integrated into standard mission operations.

## 6. CONCLUSIONS

In summary, AEGIS enables autonomous recognition of scientifically interesting targets in MER rover navigation camera imagery. These targets can then be

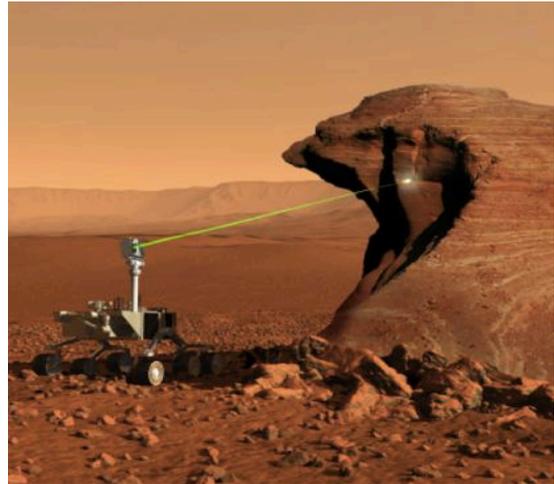


Figure 5. Artist's illustration of the Mars Science Laboratory (MSL) Rover ChemCam Spectrometer. ChemCam is a Laser Induced Breakdown Spectrometer that can identify elemental composition information on rocks and soil. Currently, AEGIS is planned for use on MSL to enable automated targeting of the ChemCam instrument.

successfully characterized without requiring a communication cycle with mission operations on Earth. New measurements with the MER Panoramic cameras 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 human operators. AEGIS was uploaded to the MER Opportunity rover in late 2009. The system has been successfully run multiple times on the surface of Mars and has consistently picked out appropriate targets. The MER mission plans to continue the use of AEGIS to enable automated targeting for the MER Panoramic camera. AEGIS is also planned for usage on the 2011 MSL Rover Mission and will collect targeted data with the MSL ChemCam spectrometer.

## 7. ACKNOWLEDGMENTS

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