RESULTS FROM THE FIRST FOUR YEARS OF AEGIS AUTONOMOUS TARGETING FOR CHEMCAM ON MARS SCIENCE LABORATORY AND NEW CAPABILITY PLANNED FOR SUPERCAM ON MARS 2020 ROVER

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ABSTRACT

The Autonomous Exploration for Gathering Increased Science (AEGIS) software system was uploaded to the NASA Mars Science Laboratory (MSL) Curiosity rover in 2015 for autonomous target selection [1]. This paper presents results from the first four years of its regular operation on Mars for autonomously selecting targets for the ChemCam remote geochemical spectrometer with a focus on the most recent findings. Results show that AEGIS has targeted highly desirable materials greater than 86% of the time versus 20% without onboard intelligent targeting. There has also been a notable increase in the rate of ChemCam observations. AEGIS is also part of surface flight software for the NASA Mars 2020 Perseverance rover. This paper describes new AEGIS capabilities that will be available for autonomously targeting the SuperCam instrument after the planned 18 February 2021 landing in Jezero crater on Mars.

1 INTRODUCTION

Robotic planetary science exploration is traditionally an iterative process where experts on Earth interpret the latest data from the robotic spacecraft and generate commands to observe targets determined to have the highest science value. These iterations, also known as ground-in-the-loop cycles, have traditionally been necessary for targeting narrow-field-of-view instruments on targets of interest. These can add one or more planning sols (days) due to one-way light times, operations schedule, and deep space communication constraints. Due to the high variance in local terrain, targeting in the blind often misses targets of interest resulting in significantly lower science return.

AEGIS performs onboard autonomous target selection by surveying targets using wide angle camera images and using criteria specified by experts to point narrow field of view instruments on the selected target for data acquisition. It provides a wide variety of options allowing operators to adjust the criteria for target selection, filtering and ranking for subsequent autonomous targeting.

2 AEGIS AUTONOMOUS TARGETING

2.1 AEGIS Usage

AEGIS was first deployed for planetary exploration on the Mars Exploration Rover (MER) mission in 2010 [2]. On MER, AEGIS was used to demonstrate the potential of the technology by pointing the narrow-field of view panoramic science camera (PamCam) on targets selected from its wide angle navigation cameras (Navcams).

A number of enhancements were made for MSL, and AEGIS has been in regular use since it was uplinked for taking narrow field of view Remote Micro-Imager (RMI) images and targeting the ChemCam (Chemistry and Camera) LIBS laser spectrometer. It has also been used to further refine RMI pointing to fine-scale features such as narrow rock veins or refine ground selected RMI pointing.

ChemCam is an instrument on the MSL rover mast [3]. It includes a Laser-Induced Breakdown Spectrometer (LIBS) that can provide remote geochemical observations at a distance of up to 7m away and a telescopic context camera, the RMI, which can take images of fine scale targets including the result of LIBS targeting. ChemCam has been valuable for both direct science observation and also as a mechanism for analyzing targets before taking more time and resource intensive complex observations with robotic arm mounted contact science instruments and sampling tools. The RMI imager has a narrow is a 20 mrad diameter, and typical ChemCam activities include a raster of LIBS points spaced at 1-2 mrad and spaning 2-20 mrad, with RMI images before, after, and sometimes mid-raster. In addition the LIBS laser must be focused precisely at the target distance to effect a LIBS measurement which requires accurate range to target. As a result, ChemCam activities were originally only targeted with operators on Earth selecting targets using previously returned wider angle Navcam stereo imagery with range data.

On Mars 2020, AEGIS can be used to target SuperCam LIBS/RAMAN and take RMI images mid-drive or post-drive without requiring ground in the loop cycles. This is particularly important on Mars 2020 which has a dedicated computer for rover navigation and is designed to drive ~300m/sol and would otherwise miss important science observations.

There are additional ways in which AEGIS may be used on Mars 2020. It is capable of selecting a target for the rover to drive to in combination with the rover Visual Target Tracking capability [6]. It is also capable of selecting a target for the rover to deploy the robotic arm on and take context images in conjunction with the go-and-hover autonomous robotic arm positioning capability.

2.2 AEGIS Processing

Core AEGIS processing is shown in Figure 8 with enhancements for M2020 that will be discussed later in the paper as shown in Figure 9. The process consists of processing a wider angle source stereo image pair. Computer vision techniques are used for target *detection[5]*. This is the process by which regions of interest are extracted from the source image as defined by user configurable parameters. The parameters are typically set to detect rock targets using an edge detection algorithm called Rockster (rock segmentation through edge regrouping). AEGIS has also been demonstrated with an alternate algorithm called TextureCam on the full scale MSL VSTB (Vehicle Sytem Test Bed), but this capability has not yet been used in flight. Image analysis techniques are then used to perform *feature extraction* on each target to quantify typical characteristics of scientifically interesting targets. The features extracted for each target include image chracteristics (such as pixel intentisty and variation of intensity), target geometry (shape, size, orientation, and smoothness of the perimeter), postion and range. User configurable criteria are then used for *target filtering* which allows excluding targets with particular characteristics such as very small targets. *Target prioritization* is then performed on the remaining targets where user configurable criteria are used to rank targets in importance based on these characteristics. The next step in the process is to *set a coordinate frame centered on the target position*. Follow-up observations are then acquired by pointing narrow field of view instruments. AEGIS can be configured at each use to perform as many science observations as desired and can use different target filtering, target ranking, or source image for each observation. For additional details see [2].

3 RESULTS FROM MARS SCIENCE LABORATORY

AEGIS has been used operationally on MSL since May 2016 (sol 1343), following installation via a software upgrade in October 2015 and a series of checkouts performed from sols 1184-1238. AEGIS provides two capabilities for autonomous targeting on MSL: identification of targets within navigation camera (Navcam) images, with a ~0.784 rad field of view, for follow-up observations with the ChemCam instrument, and identification of targets within the ChemCam Remote Micro-Imager (RMI) camera images, with a ~0.020 rad field of view, for pointing refinement of small targets such as bright veins (Figure 8).

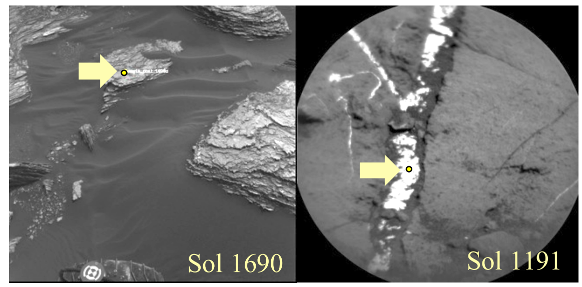

Figure 1: AEGIS finding outcrop in a Navcam image (left), and finding a vein in an RMI image (right).

Below, we focus on the most commonly used of these capabilities, the identification of targets in Navcam images, which has been used 237 times between sols 1343-2830 to identify 284 targets.

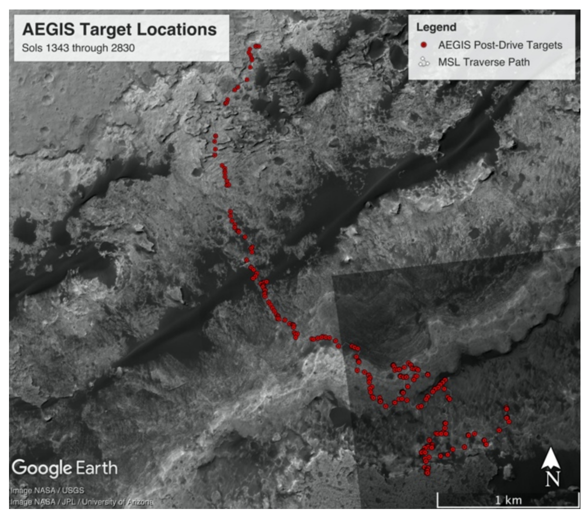

Figure 2: Locations of AEGIS targets from the first 4 years of use on MSL in Gale Crater, Mars (sols 1343-2830).

Figure 9 shows a map of AEGIS targets identified along MSL's traverse through Gale Crater from sols 1343 to 2830 as it explored transitions between several geologic units, including diverse exposures of mudstones and sandstones of varying composition [4].

Overall, AEGIS has demonstrated its ability to successfully identify targets in Navcam images efficiently across diverse terrains and under a variety of illumination conditions.

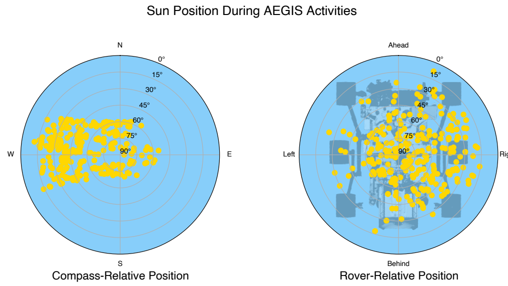

Figure 3: Sun Position During AEGIS Activities

Figure 3 shows the position of the sun during AEGIS activities, both in compass-relative and rover-relative frames. Due to typical driving schedules, most post-drive AEGIS activities are performed in the afternoon when the sun is in the western half of the sky, but because the rover changes orientation frequently, illumination conditions relative to the rover have varied widely above 15 degrees in elevation. In all cases, AEGIS has been able to visually identify a set of targets in images, usually in under 500 seconds, using the spacecraft's limited RAD750 flight processor.

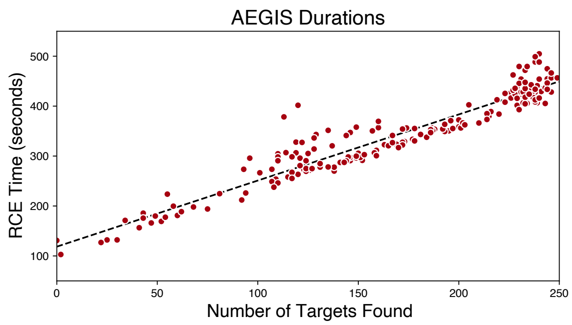

Figure 4: AEGIS Durations through Sol 2830[1].

Figure 4 shows that the duration of AEGIS activities is dependent on the number of targets found, since each target requires stereo computation and visual feature extraction for ranking and filtering. Cases where AEGIS has identified no targets are limited to events of accidental instrument mis-pointing; a fault in the rover's remote-sensing mast in one case led to a Navcam source image of the sky, in which no targets were found. In another case, the image was centered on the rover's robotic arm; targets on and near the rover in image space are prohibited, so no allowable targets were found. In a single case, the rover's entry into a new geological unit resulted in AEGIS finding no targets which met user specifications for science suitability, so no measurements were made; these specifications were updated for future runs to widen the range of allowable targets in the new terrain.

In addition to the practical considerations discussed above, the real test of an autonomous targeting system like AEGIS is whether it enhances mission science. Both an empirical study of AEGIS results as well as anecdotal experiences of use during mission operations suggest that this is in fact the case.

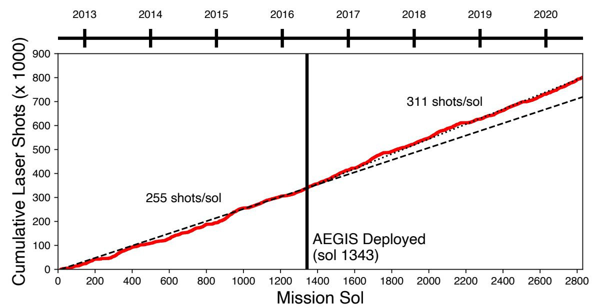

Figure 5: LIBS Shots through Sol 2830

First, Figure 5 shows the number of measurements made with the ChemCam instrument in terms of the cumulative number of LIBS laser shots made throughout the mission. Since AEGIS deployment, the average rate of LIBS measurements has increased from 255 shots per sol to 311 shots per sol. While there could be several reasons for this increased rate of measurements, at least one reason is that AEGIS increases the opportunities for ChemCam measurements to be made during times after drives before ground-based targets have been selected within post-drive imagery. In fact, AEGIS was cited by the MSL project leadership in their recent submission for extended mission funding as a key capability leading to increased mission productivity over time.

In addition to the increased quantity of ChemCam measurements that AEGIS enables, it also increases the quality of these measurements relative to a baseline approach previously used in the mission called "blind targeting." The blind targeting strategy involved measuring a point with ChemCam that is at a fixed direction in azimuth and elevation relative to the rover body. As the name suggests, this strategy is done without knowing the type of target present at the location at this fixed rover-relative position. Therefore, blind targeting often measures a target with lower scientific relevance and value than one identified visually. Figure 6 shows an empirical comparison of the target types identified by AEGIS on the sols it was used, versus the target types that would have been

[1] Excludes sols with multiple AEGIS runs

measured with blind targeting on those same sols. Outcrop and Rock are typically more desirable targets than Sand and Soil, and these types are measured over 90% of the time with AEGIS versus less than 40% of the time with blind targeting.

As further evidence of the science value of targets selected autonomously by AEGIS, the system has in several cases selected targets on the same individual rocks as were chosen by the science team. For example, due to communication schedules, AEGIS' top-ranked target from the sol 2362 run was not yet downlinked when the rover's activities for sol 2363 were planned.

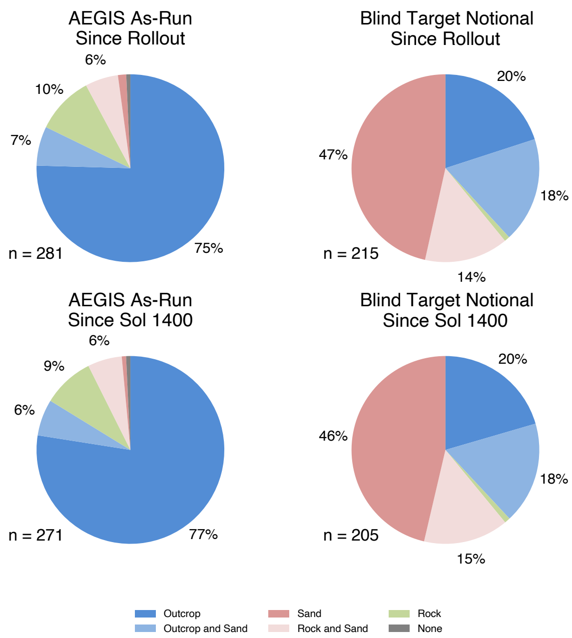

Figure 6: Target Type Percentages through Sol 2830

The science team chose to make the bulk of their observations for sol 2363 on what turned out to be the same rock AEGIS had also ranked as the best science target -- the positions of the AEGIS- and human-targeted ChemCam observations differ by less than 3 milliradians (Figure 7). In a number of other cases, more promptly-downlinked ChemCam spectra from AEGIS targets have prompted the science team to follow up on interesting discoveries with additional measurements.

AEGIS' reliability at selecting quality geochemistry targets has led the science team to make use of it when rover resources are constrained, or when driving progress is a priority. The team can, and often does, reduce the time and power spent on ground-targeted observations, and spend them instead on driving or other activities, knowing that AEGIS will reliably find representative rock targets for the geochemical survey along the rover's traverse.

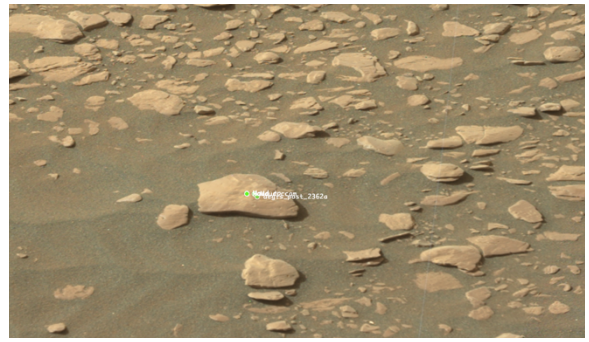

Figure 7: View from the MSLICE operations planning software of Mastcam mosaic showing targets selected by the science team on sol 2363 and by AEGIS on sol 2362.

During such mission phases, AEGIS is sometimes responsible for the majority of ChemCam targets for periods of a few weeks. Since AEGIS can be used with a consistent target profile that favors the background outcrop materials, this strategy also allows the science team to focus their attention on anomalies, oddities, or other salient features, while AEGIS conducts the baseline survey.

AEGIS has also proven useful in a number of unexpected circumstances where humans were unable to perform ground-in-the-loop targeting. On several occasions, the post-drive Navcam images used by the science team for instrument targeting have been delayed in their delivery by interplanetary communications problems of one kind or another, and AEGIS has been used to take ChemCam measurements of multiple targets as a replacement for ground-targeted measurements which would ordinarily have been planned. In another case, terrestrial communications were the problem; remotely-located instrument operators were unable to obtain the images from JPL's servers on sol 1672 and could not perform instrument targeting, so the operators used AEGIS to study a workspace they could not see. As another example, the science team has twice elected to run AEGIS during December holiday operations stand-down periods to take ChemCam measurements autonomously on as many as six targets at a single location, while the science team enjoyed a rest from their work.

Overall, the experience using AEGIS on MSL has been successful both operationally and in terms of the increased scientific data collection it has enabled. We look forward to continued use on MSL and adapting our experience to the Mars 2020 rover at Jezero Crater.

4 MARS 2020 CAPABILITY

The Mars 2020 implementation of AEGIS includes several improvements to operability and performance. In terms of operability improvements, on MSL, AEGIS was only able to analyze newly acquired images. For Mars 2020, AEGIS includes the ability to analyze previously acquired images. This saves time and data volume because typically operators want to apply AEGIS to scenes that have already been imaged for other purposes. In addition, Mars 2020 AEGIS has the ability to remember information about identified targets across rover sleep cycles, making it easier for operators to schedule follow-up observations for those targets. The performance improvements for AEGIS include increased pointing accuracy by leveraging a Mars 2020 capability for closed-loop pointing of the mast via vision-based feedback, and increased computational performance by reducing the amount of stereo calculation required.

4.1 Operability improvements

4.1.1 Image retrieval

In the AEGIS autonomous targeting process on MSL, the initial step in the process is acquisition of the wider field of view source image, as shown in Figure 8. On M2020, as shown Figure 9, the initial step is to retrieve a previously acquired stereo image pair. The retrieved source image is used for subsequent target detection and AEGIS processing.

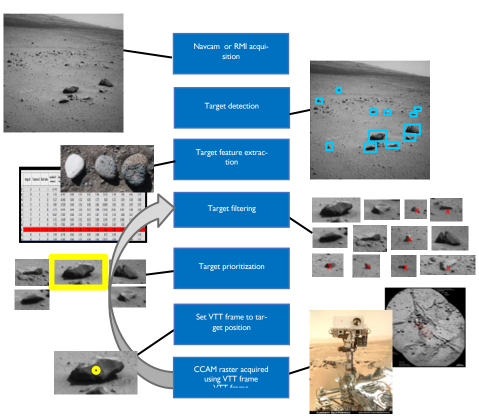

Figure 8: Operational MSL autonomous target processing

This allows utilizing autonomous AEGIS targeting on images taken for other science and engineering purposes including, for example, rover navigation and visual odometry. The image retrieved need not be the immediately preceding image. The image to be retrieved is specified using a sequence identifier, a command number range within that sequence, and an absolute or relative time period from which to retrieve the image. If multiple images satisfy the conditions, then the most recent image from the subset of images is selected.

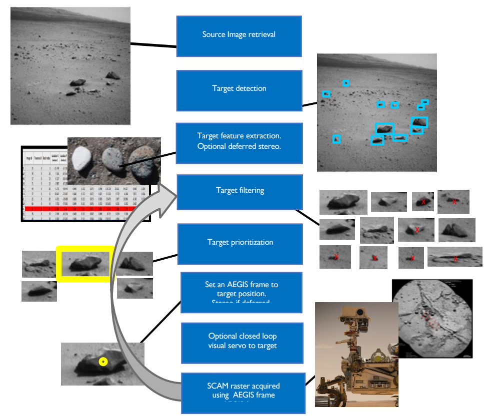

Figure 9: M2020 autonomous target processing

Targets in the robotic arm workspace are often occluded from the Navcam stereo coverage with the robotic arm stowed. In addition to the images from the mast mounted navigation cameras (Navcam images), images from the front or rear hazard cameras (Hazcams) can also be used for AEGIS processing on M2020. Often relatively low-cost geochemical data from a remote spectrometer like SuperCam is used to weigh the science value of the target versus expending additional resource cost such as operations planning and flight execution time, energy, and data volume of deploying the robotic arm and positioning arm mounted instruments. AEGIS processing can be run by retrieving the actual image taken for ground based robotic arm positioning. AEGIS can then acquire SuperCam RMI and LIBS data of the highest potential targets in the workspace, so this decision can be made without the cost of an additional ground in the loop cycle.

4.1.2 Nonvolatile AEGIS frames

Mars 2020 AEGIS has the capability to remember information about identified targets across rover sleep cycles, making it easier for operators to schedule follow-up observations for those targets. MSL and M2020 are power limited and rover naps and overnight sleep cycles are used to recharge the batteries. Because the compute element is reinitialized after each sleep cycle, this prevents the use of any data, including AEGIS targeting data, that was not saved to nonvolatile memory. On M2020, AEGIS has five dedicated nonvolatile frames for storing all the information necessary for taking follow-up observations. As a result, AEGIS target finding and feature extraction (the most resource intensive parts of the process) are not required to be repeated after a sleep cycle, which allows more operational flexibility. Follow-up observations on autonomously selected AEGIS targets can continue to be performed after a shutdown and wakeup and even across sols. In addition to all the basic information included in every frame in the flight software frame tree, AEGIS frames include metadata needed for pointing the mast for follow-up observations and for correlating the observations with the source image and target features. This metadata includes rover motion counters that are used to verify that the rover has not moved since the AEGIS frame was stored, which would invalidate the targeting information.

4.2 Performance improvements

4.2.1 Closed loop pointing

Limits in targeting accuracy, including motor backlash, motor control error, resolver accuracy, thermal effects, and rover settling or shifting, contribute to uncertainty in targeting of ±6 mrad. These can be reduced by commanding compensations to ±2 mrad. LIBS rasters typically have a point spacing of 1-2 mrad and span of 2-20 mrad. Hence, the uncertainty is significant.

AEGIS leverages the Mars 2020 closed-loop pointing capability to achieve precise pointing for follow-up observations. Closed-loop pointing uses vision and resolver-based feedback to correct positioning. It is designed to achieve 1mrad pointing accuracy. When using closed-loop pointing for follow-up observations, AEGIS provides the target's inscribed circle centroid pixel in the source image and the range to the target. The vision-based pointing correction uses image comparison to eliminate pointing error. The range to target is used to compensate for parallax if the feedback imager is not the imager that is being pointed. Closed-loop pointing moves through a series of waypoints to approach the target, using guidance and feedback until the boresight is aligned with the target. Mars 2020 also includes onboard pointing guidance capability to mitigate the effect of the actuator backlash on pointing accuracy by modeling backlash disturbances and guiding the actuator slew through a kinematic path where the backlash can be controlled.

4.2.2 Stereo optimization

For feature extraction, AEGIS performs stereo analysis on the source image. Stereo is used to provide the distance to the target and three-dimensional size and position of the target in the rover coordinate frame. As shown in Figure 8, on MSL, this information was previously computed for each target during feature extraction and may be used for filtering and ranking targets. For example, the distance-to-target can be used to filter targets that are outside the LIBS firing range (2.2m-7m). This information is also used to set the target frame coordinates and provides the range for follow-up observations. Given the limited computation available on the radiation hardened RAD 750 flight processor, AEGIS uses the point stereo algorithm to perform stereo at only the inscribed circle center of the feature. In current MSL operations, stereo still takes on the order of a second per target with a few seconds of setup. When computing point stereo for up to 255 targets, this can add significant duration.

Mars 2020 improves time-performance in this area. As shown in Figure 9, on Mars 2020, AEGIS stereo may optionally be deferred to the target selection step, instead of performing stereo on the full set of targets during feature extraction. If deferred stereo-based filtering is requested, the request is cached. Stereo is later computed on a per-target basis when a request is made to set an AEGIS frame on a target. If stereo cannot be computed, the target is filtered as unusable, and stereo is computed for the new target at the specified rank. Previously, on MSL, this filtering would have occurred during feature extraction if stereo could not be computed for any reason, such as no overlap between images. On Mars 2020, the cached filtering is performed at the target-selection stage, and if the target becomes filtered, the next target with the specified rank is processed until the frame is set on a target. The number of stereo computations performed depends on the scene but is significantly reduced by avoiding stereo computation on poorly-ranked targets per filter and rank criteria. Analysis of past data from MSL shows that this would save on the order of 120 seconds over all AEGIS processing and targeting per source image.

The capability for saving AEGIS frame information across sleep cycles and the option for stereo optimization may also be included in future flight software updates on MSL.

5 DISCUSSION

AEGIS has become an important part of MSL science operations. Post-drive autonomous targeting is used regularly. The science and engineering operations team have developed template configurations applicable to classes of terrain that require minimal operational overhead from adding autonomous AEGIS targeting to a plan. The operability and performance improvements on Mars 2020 will result in lower resource consumption while improving accuracy, thus providing increased opportunities for additional AEGIS observations.

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