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AEGIS Autonomous Targeting for the SuperCam Instrument on the Mars 2020 Perseverance Rover

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Abstract

The AEGIS (Automated Exploration for Gathering Increased Science) intelligent instrument targeting software system is used aboard NASA's Mars rovers to autonomously select targets for science instruments, and collect such data without Earth in the loop. This capability is especially useful in periods where human operators on Earth have not yet received image information to allow human-guided instrument targeting. After successful demonstration on the MER Opportunity rover, and extensive use aboard the MSL Curiosity rover, in 2022 AEGIS was deployed to the Mars 2020 Perseverance rover, for targeting the SuperCam remote spectrometer instrument. AEGIS has seen extensive use on Mars 2020, collecting scientific measurements on over 150 targets as of submission. The new capabilities of SuperCam compared to previous instruments have allowed 1) a greater range of scientific data to be collected, and 2) new AEGIS features added since the initial Curiosity deployment have allowed the science and operations teams to more quickly react to information about AEGIS-selected targets, leading to beneficials adjustments in strategies for human-selected targets in response. AEGIS has performed well in selecting desirable science targets even as the Perseverance rover has made rapid progress across many kilometres over several types of new terrain.In some phases of the mission AEGIS has acquired the majority of geological/geochemical measurements, when mission circumstances constrained human-targeted science observations. We report on the deployment timeline and strategy, adjustments and enhancements to AEGIS compared to the 2015 Curiosity deployment, statistics and performance of the system in-situ on Mars, and notable results from AEGIS on Perseverance.

Introduction

The Mars 2020 mission operates the Perseverance rover on the surface of Mars, in and near Jezero crater [1]. The mission has key goals including geological study of the crater's materials as part of a campaign of selecting, and collecting, rock samples for potential return to Earth as part of the Mars Sample Return program. To support these geological investigations, the rover carries a payload suite including a range of scientific instruments for remote, proximity, and environmental observations.

Among these instruments is SuperCam [2][3], which is capable of a range of sensing modes, including Laser-Induced Breakdown Spectroscopy (LIBS), Visible and Near-Infrared reflectance spectroscopy (VISIR), Raman spectrosocopy, Time-Resolved Luminescence Spectroscopy (TRLS), as well as imaging with a telescopic camera called the Remote Micro-Imager (RMI) and a microphone. SuperCam is used to observe nearby materials and measure the physical, chemical, and mineralogical properties, with the various sensing modes being effective at ranges from tens of centimetres to a few kilometres. One common measurement type combines LIBS and VISIR measurements on several points rastering over a small distance (on the order of a few centimetres) on a rock surface some 2-7 metres away, with before and after images of the rock surface using the RMI, and microphone recording of the LIBS shots. In some cases the VISIR mode is omitted. Such measurements, known in shorthand as "LIBS-VISIR rasters" or "LIBS rasters", are made in the majority of uplink plans for the rover, and are an important part of the mission scientific work of characterizing the geochemical composition of the exposed rocks in Jezero crater, along with its spatial variation.

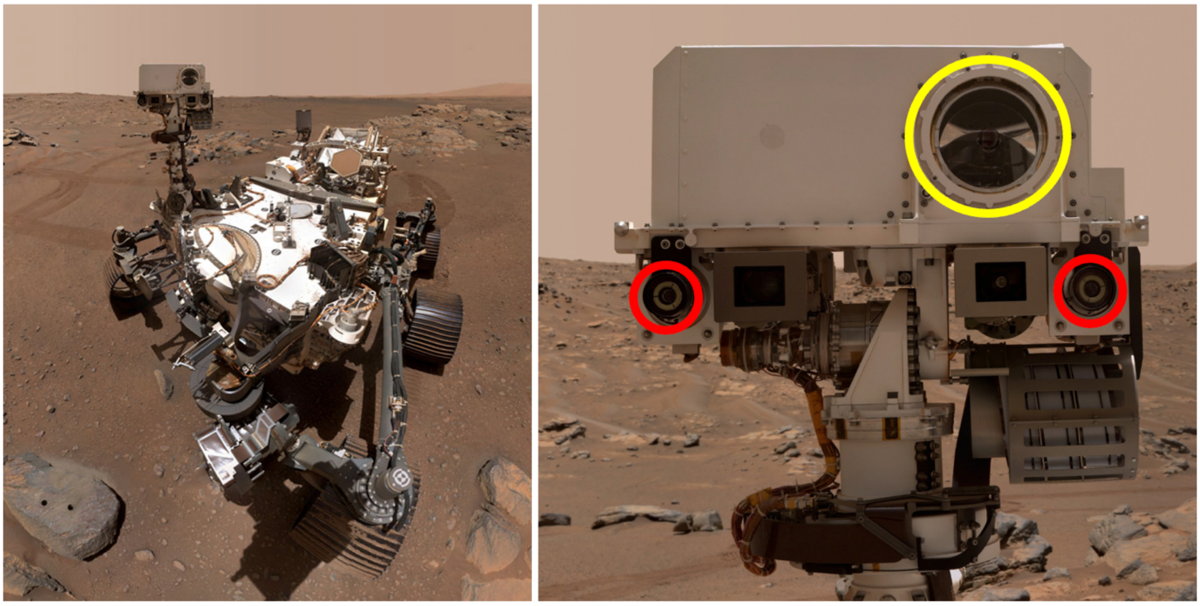

Figure 1- Perseverance rover on Mars (left), and close-up of the Remote Sensing Mast with SuperCam window marked in yellow and stereo NavCams marked in red (right). Image acquired on Mars 2020 sol 198. Credit: NASA/JPL-Caltech/MSSS

LIBS-VISIR rasters must be specifically targeted at features of interest on the Martian surface, since the spatial coverage of each LIBS point in the raster is on the order of 1-2 mm, and the whole raster itself may cover only a few cm. A successful observation depends on the SuperCam telescope being correctly focused on the target, and although the instrument does have an autofocus capability, it is still necessary to provide a reasonable estimate of the range to the target to 'seed' the autofocus search algorithm. For these reasons, SuperCam targets are typically selected by operators on Earth using images from the rover's navigation cameras (NavCams). The NavCams are stereo colour imagers mounted on the rover's Remote-Sensing Mast (RSM) near the SuperCam aperture, allowing NavCam images to be used to recognize potential targets for SuperCam and compute the distance to them. Images used for targeting must have been acquired after the most recent time the rover has driven, so that their view of the target matches that of the rover at the time of the SuperCam observation being planned. Such images are thus sometimes termed "post-drive imaging" (PDI).

The long light-times to Mars and the rotation of the planet lead to mission designs in which commands are nominally uplinked to surface platforms once per Martian solar day (sol), at a time early in the sol when Earth is in the sky at the landing site, and this practice is in use for Mars 2020. This means that if the operations team commands the rover to drive on a given sol, any targets selected they have selected for SuperCam must be observed before the drive begins.

The team may select targets at the rover's end-of-drive location after the drive has completed and new post-drive NavCam images have been acquired and downlinked to Earth. The commands for SuperCam targets at this new location would be included in the next uplink plan, typically on the next sol (though operations schedules and unexpected interruptions can mean the next plan is uplinked more than one sol later).

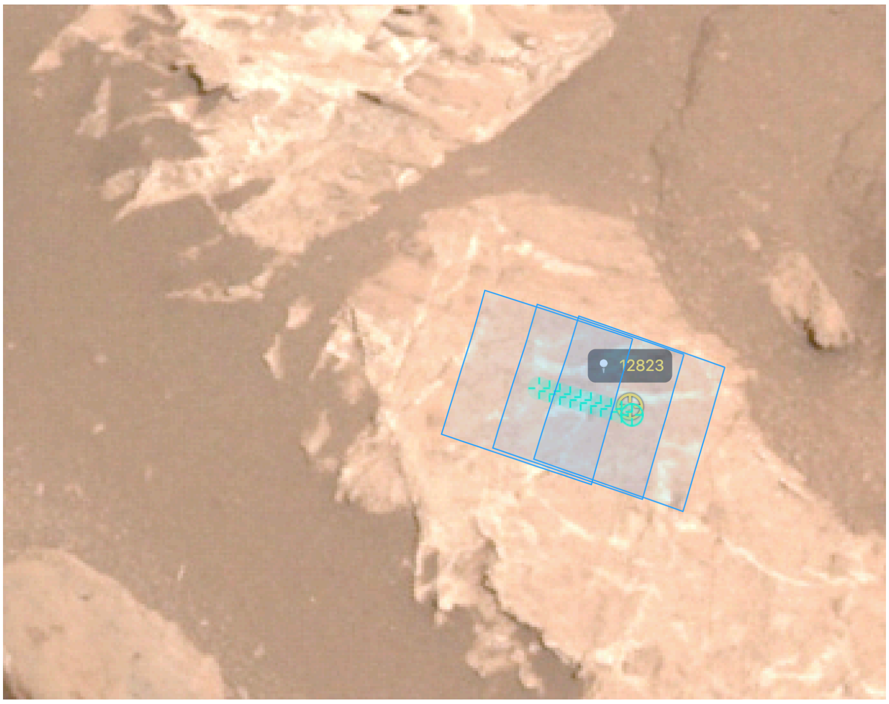

Figure 2 - Example of targeting a rock feature with SuperCam using visualization of the post-drive NavCam images and a projection of the SuperCam LIBS/VISIR points (green crosses) and RMI images (blue frames). The point 12823 is a selected rock position for targeting planning; its number is merely for identification during planning.

It is often the case that there is time after the drive, but before the next uplink, for science observations such as SuperCam LIBS-VISIR rasters. However, without the ability to select targets, this post drive time cannot be used for such 'targeted' observations.

AEGIS

AEGIS (Autonomous Exploration Gathering Increase Science) is a software system which is used aboard Mars rovers to allow autonomous onboard target selection for science instruments. Developed at the Jet Propulsion Laboratory, it was tested aboard the Mars Exploration Rover (MER) Opportunity in 2010, selecting targets for the Pancam instrument. Since 2016, AEGIS has been in regular use aboard the Curiosity rover, selecting targets for the ChemCam instrument [4], where it has significantly added to the Mars Science Laboratory (MSL) mission's geochemical survey in Gale crater. This paper describes the use of AEGIS aboard the Perseverance rover, where it has been selecting targets for SuperCam since 2022.

AEGIS acts as the rover's autonomous target selection system. The process begins with acquisition of a NavCam stereo image, termed the source image. AEGIS processes the source image and uses a custom algorithm to identify rock targets within it. Currently, the Rockster algorithm is used, which conducts edge-finding and edge-grouping operations, as well as other image-processing steps, to identify rock targets [5]. AEGIS then extracts visual properties from each of the targets found, using the information in the pixels within the target. The targets are then filtered and ranked according to various criteria which can be adjusted for each run of AEGIS, including (among others) size, brightness, shape, distance from the rover, and orientation in the field of view. These parameters can be selected at uplink to favour different types of targets or to adapt to different expected scenes. After target finding, filtering, and ranking, one or more top-ranked targets are selected. A co-ordinate frame is defined at the centroid of each selected target. Then, either immediately, or at a later time which is suitable, SuperCam observations (typically a LIBS-VISIR raster) are made on each target, by pointing the instrument with reference to the target co-ordinate frame.

The process for AEGIS target-finding is illustrated in Figure 3.

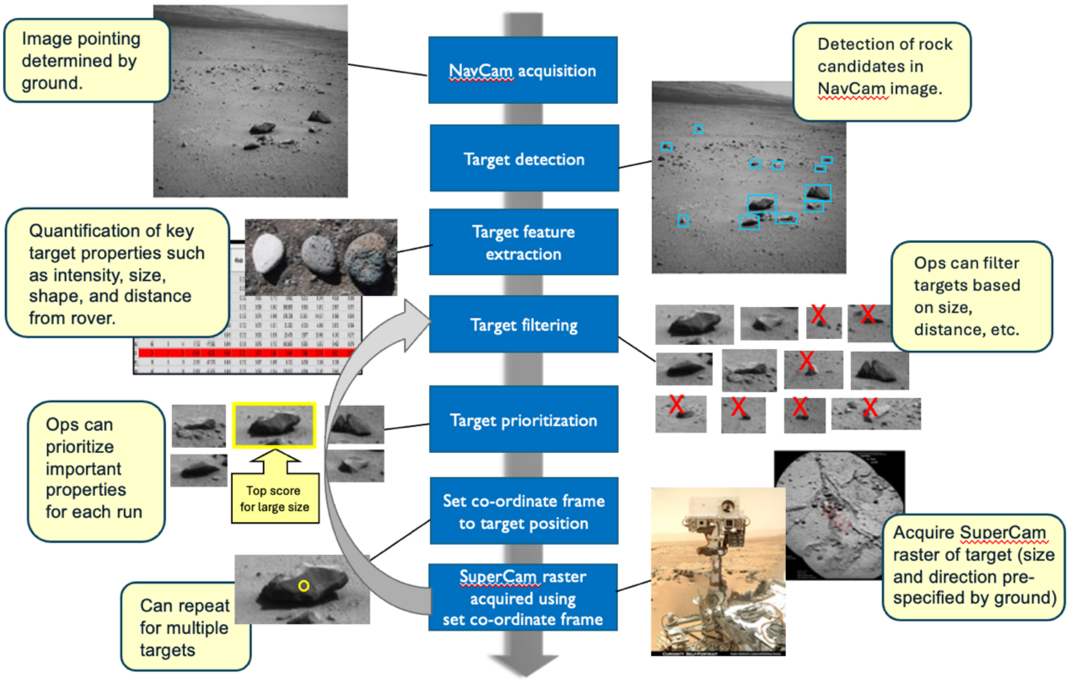

Figure 3 - AEGIS onboard workflow

Safety considerations

Autonomous instrument targeting for SuperCam involves a number of operations which could pose potential risks if not conducted correctly and reliably. For example, the rover's remote sensing mast is articulated in both of its degrees of freedom, the SuperCam instrument is powered on and placed in its active mode, the SuperCam focus stage is moved, and the powerful LIBS laser is activated and fired, typically 300 times per target. It is important to protect the SuperCam instrument, and the rover generally, during all operations. One notable risk in SuperCam targeting is sun-safety – the SuperCam instrument can be damaged if pointed too close to the sun during or between observations. Another is laser safety – the LIBS laser is powerful enough to turn part of a solid rock surface into plasma, and to leave small pits in its titanium calibration target. It is thus important that SuperCam does not inadvertently target the rover hardware, to avoid damage to the rover or its science instruments. There are a range of risks associated with any software-controlled operation if unexpected behaviours emerge from the use of the software. Finally, there is a risk of lost science observations if a SuperCam observation is improperly pointed, or poorly focused. In human-selected targeting, these risks are mitigated with human oversight, procedural controls, and software controls. In AEGIS autonomous targeting, much of the same is true, though certain additional controls are in place.

The AEGIS flight software was subjected to an extensive program of testing, verification, and validation. This program relied in part on work done for the MSL deployment, but also included new testing, both in software test venues and the Mars 2020 Vehicle System Testbed, a near-complete hardware simulator of the Perseverance rover. The first AEGIS operations on Perseverance itself were also subject to detailed review and conducted in stages, with basic operations being undertaken initially, before an expanded deployment some months later.

The rover's own flight software includes protections against mispointing SuperCam, both for sun-safety and for laser collision with the hardware. The flight software will deny commands which move the SuperCam focus stage if the instrument is pointed in a sun-unsafe region, and will deny sun-unsafe pointing commands if SuperCam is not in its sun-safe focus position. Similarly, if SuperCam is pointed such that the laser beam would intersect the rover (or a safety margin volume around the rover), commands to fire the laser are denied. In the event one of these safety actions is triggered, the SuperCam observation in question would be wholly or partially prevented, resulting in a loss to mission science (but protection of the instrument and rover hardware). To avoid triggering these protections, AEGIS includes its own internal checks, preventing it from selecting targets which are in sun-unsafe or collision-unsafe zones. In this way, targets are not selected which would trigger the rover system-level protections, and the loss to science is avoided. As a result, to date aboard Perseverance, no AEGIS operation has triggered rover-level protections, and no sun- or collision-unsafe command has been sent to the rover or instrument. The rover-level protections remain in place, and all commands, including AEGIS commands, are checked, to provide an extra layer of safety.

When AEGIS performs its collision check, it uses the actual state of the rover's various mechanisms, including an articulation model of the rover's suspension elements and robotic arm. If, after selecting its target, the rover were to drive before an attempt to measure the target with SuperCam, the relative motion between the target and the rover could bring the target into a position where sun an collision safety checks are no longer valid. Similarly, if, after selecting a target, the robotic arm were to move to a new position, the target might now be in collision (for example if the arm were to move into a position between the SuperCam aperture and the target). For these reasons, AEGIS includes checks at the time of the SuperCam observation of the AEGIS-selected targets which prevent the use of these targets if rover mechanisms such as the robotic arm or mobility system have moved since the target was selected.

For measurements on AEGIS-selected targets, the SuperCam operations themselves are very similar to those for human-selected targets. The operations team selects instrument parameters in the same way and prepares command sequences using the same tools. The inputs to the AEGIS targeting itself have been designed so that the operations team has minimal additional work to enable autonomous targeting; in general only the direction to point the source image must be selected, and a few key parameters verified. Certain additional rules must also be checked, such as ensuring that activities which would invalidate the selected targets are not scheduled between target-finding and SuperCam observations of the targets. These conditions, as noted above, are checked on-board at run time, but if these checks catch a problem, the observation will be lost; during uplink operations planning, such outcomes can be avoided by ensuring the uplink plan is built in a way which does not creates these conflicts.

Timeline of deployment

What follows is a timeline of key dates for deployment of AEGIS to the Perseverance rover. For each event, the mission sol on which the activity in question executed on Mars is given, along with the Gregorian calendar date of the uplink planning for the activity.

The Perseverance rover landed in Jezero crater on February 18th, 2021 (sol 0). SuperCam began making LIBS measurements of rock targets on sol 12 (March 2nd, 2021). Several tests of AEGISwere made on Mars between on sol 383 (March 18th, 2022), and sol 442 (May 16th, 2022). The initial deployment of AEGIS, with standardized commanding and basic features, was first used by the operations team on sol 449 (May 24th, 2022). An expanded deployment, with adjustable parameters for AEGIS and for the SuperCam observations on the AEGIS targets, was deployed in early 2023 and first used on sol 698 (February 2, 2023).

Results – Target selection parameters

The collection of Rockster target-finding and AEGIS filter and rank parameters used is termed the 'scene profile', and can be adapted as necessary as the rover explores new types of terrain, or to favour different types of rocks. The scene profile can be adjusted at each uplink, but experience has shown that a robust scene profile adaptable to a variety of terrains can be selected and used for long periods. The default profile in use on Perseverance is designed to favour light-toned outcrop; usually the in-place rock is lighter than the regolith surrounding it. This profile also performs well in scenes where outcrop is absent or sparse, where it will commonly select a float rock (a geological term referring to a rock sitting loosely on or at the surface, rather than being in-place where it formed or lithified again into a conglomerate). In some scenes, especially where outcrop is absent and float rocks are few, small, dark, and/or shadowed, the default scene profile (set to favour light-toned-outcrop) will select light-toned regolith between the float rocks which has been included in a target trace by the Rockster algorithm. Though not the favoured choice of material, such a selection still results in a SuperCam measurement of the regolith (and indeed, the SuperCam team does periodically choose to make regolith measurements as part of the scientific investigation of Mars surface materials). Such regolith measurements occur in a small minority of cases, their occurrence varying with the terrain the rover drives over. Regions with sparse rock give more frequent regolith results, and they also appear to occur more frequently when the regolith has a rougher visual texture; this may be due to the Rockster edge-finding algorithm finding more, and more enclosable, edges in such rougher terrain.

In a small number of cases AEGIS has not selected a target at all. This can occur if all of the targets found are filtered out by the scene profile (for example if they are too small to accommodate a SuperCam raster), or if they are not within a suitable range for the SuperCam laser, or if the range estimate quality is poor. When AEGIS does not select a target, no co-ordinate frame is placed, and the SuperCam observation is not attempted. In one notable case, an autonav drive (in which the rover selects its own safe path towards a defined goal) ended with the AEGIS source image pointing to the west, and the rover stopped on a slope so that the camera was tilted upward enough for the sun to be in the NavCam field of view at the time the AEGIS source image was taken. This especially poor lighting led to very few targets being found, and all of those found being filtered out for poor stereo range confidence. The operations team deliberately pointed the source image such that (even with autonav driving) it would be more typically pointed away from the western direction on subsequent sols during that drive campaign, to avoid a recurrence of the poor lighting.

Results – Science Team Use

Other than the source of the target selection, AEGIS-targeted observations are acquired with the same SuperCam parameters, and in the same manner, as human-targeted observations. The resulting scientific data are thus directly comparable, and the science team makes use of data from both categories of targets in their analyses. AEGIS-selected targets are regularly presented and discussed in science team meetings. Indeed, the additional measurements provided by AEGIS autonomous targeting have in some cases led to significant scientific results [6].

It has become routine for the science team to include AEGIS-targeted activities in most uplink plans where a drive occurs. AEGIS is usually included unless available energy is very limited, or other occasional post-drive activities compete for the time when the SuperCam observations of the AEGIS target would need to run.

Given the nature of the Mars 2020 strategic exploration plan, which requires the rover to cover large distances, there are many uplink plans with drives, and driving often dominates the time in the plan, sometimes at the cost of reducing pre-drive targeted SuperCam observations. This creates an important utility for AEGIS to make up for a lack of human-targeted observations. In recent drive campaign, the rover drove 2.44 km from a locality called Bunsen Peak to one called Bright Angel, over an 83-sol period from sol 1092-1175. The rover team prepared 48 uplink plans during this period, and AEGIS targeting was used in 45 of them. In 35 of those plans, AEGIS was responsible for half or more of the LIBS-VISIR targets observed, and in 12 plans, AEGIS selected all of the targets. Overall, in this period, SuperCam measured 112 LIBS-VISIR targets, with 56 each selected by the human team and by AEGIS.

Since AEGIS rollout, as of this writing (Sept 25th, 2024), AEGIS has selected 170 targets for SuperCam, and remains in routine use by the science team.

Conclusion

AEGIS has proven effective and scientifically useful on the Mars 2020 mission, and is contributing a significant fraction of the targets observed by the SuperCam instrument. The science team routinely elects to include AEGIS autonomous targeting in the plans uplinked to the rover, and we expect continued regular use of the capability. The AEGIS team will continue to identify opportunities to refine and improve the capability, and to introduce it to additional missions where autonomous feature recognition and instrument targeting.

References

[1] Farley, K., Williford, K., Stack, K., et al. (2021) Mars 2020 Mission Overview. *Space Science Reviews* 216, 142

[2] Maurice, S., Wiens, R. C., Bernardi, P., Caïs, P., Robinson, S., Nelson, T., et al. (2021). The SuperCam Instrument Suite on the Mars 2020 Rover: Science Objectives and Mast-Unit Description. *Space Science Reviews* 217, 47

[3] Wiens, R.C., Maurice, S., Robinson, S.H., Nelson, T., Cais, P., Bernardi, P., et al. (2021) The SuperCam Instrument Suite on the NASA Mars 2020 Rover: Body Unit and Combined System Tests. *Space Science Reviews*. 217, 4.

[4] Francis, R., Estlin, T., Doran, G.; et al (2017) AEGIS autonomous targeting for ChemCam on Mars Science Laboratory: Deployment & results of initial science team use, *Science Robotics*, vol 2, iss 7

[5] Burl, M., Thompson, D.R., deGranville, C., and Bornstein, J. (2016) Rockster: Onboard Rock Segmentation Through Edge Regrouping, *J. Aerospace Info. Sys*. 13, 8

[6] Beck, P., Dehouck, E., Beyssac, O., Bernard, S. et al, SuperCam detection of hydrated silica in the Jezero crater, *Earth and Planetary Science Letters* (submitted)

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Dan Gaines is a Principal member of JPL's Artificial Intelligence Group. He was the Deputy Cognizant Engineer for Mars 2020 Flight Software and lead flight software developer for AEGIS on the Curiosity Rover. Dan has developed flight software for the MER, MSL, Mars 2020 & Europa Clipper missions and has performed operations for MER, MSL & Mars 2020.

Tony Nelson is an operations lead for SuperCam at Los Alamos National Laboratory. Over his career, he has been a lead engineer for spectroscopy electronics design for the ChemCam, SuperCam, and SHERLOC instruments, and has developed single board computers for numerous space flight missions.

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