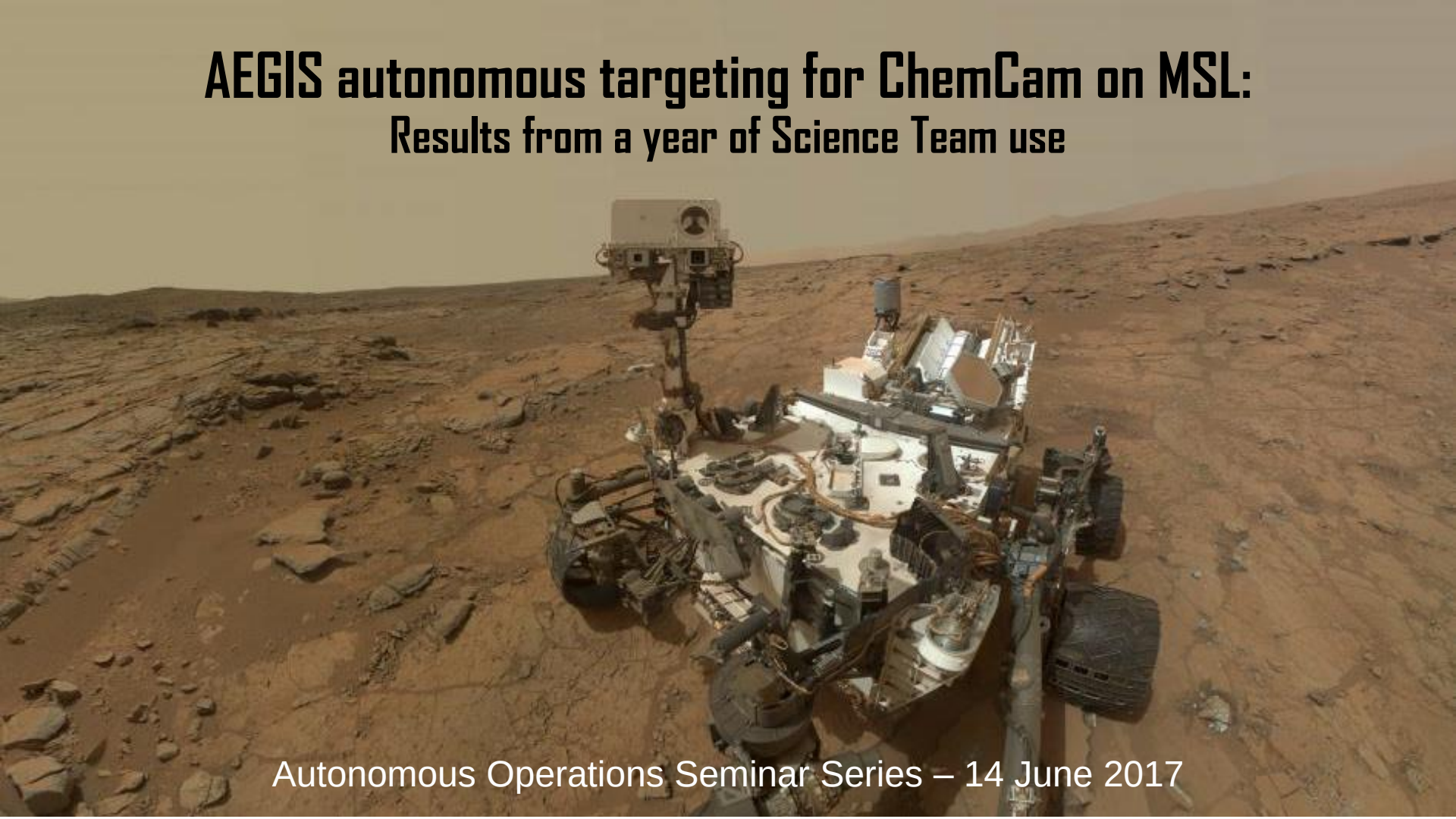
AEGIS autonomous targeting for ChemCam on MSL:
Results from a year of Science Team use



Autonomous Operations Seminar Series – 14 June 2017

Raymond Francis

Jet Propulsion Laboratory,
California Institute of Technology

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Introduction to AEGIS

AEGIS is:

An **intelligent software** system

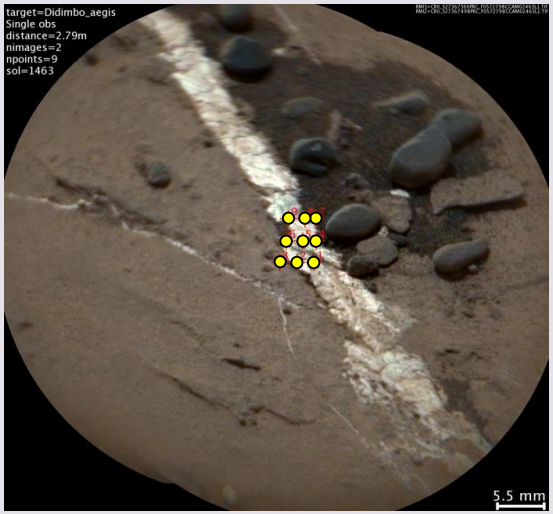
Running since 2016 **on-board** the *Curiosity* rover

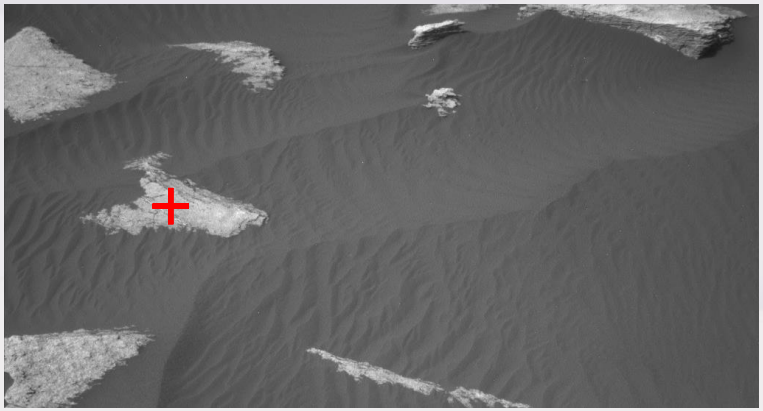
Autonomously choosing science targets and measuring them with the ChemCam laser spectrometer instrument

Favouring targets based on **scientists' preferences**

Regularly, reliably interpreting **complex natural scenes**

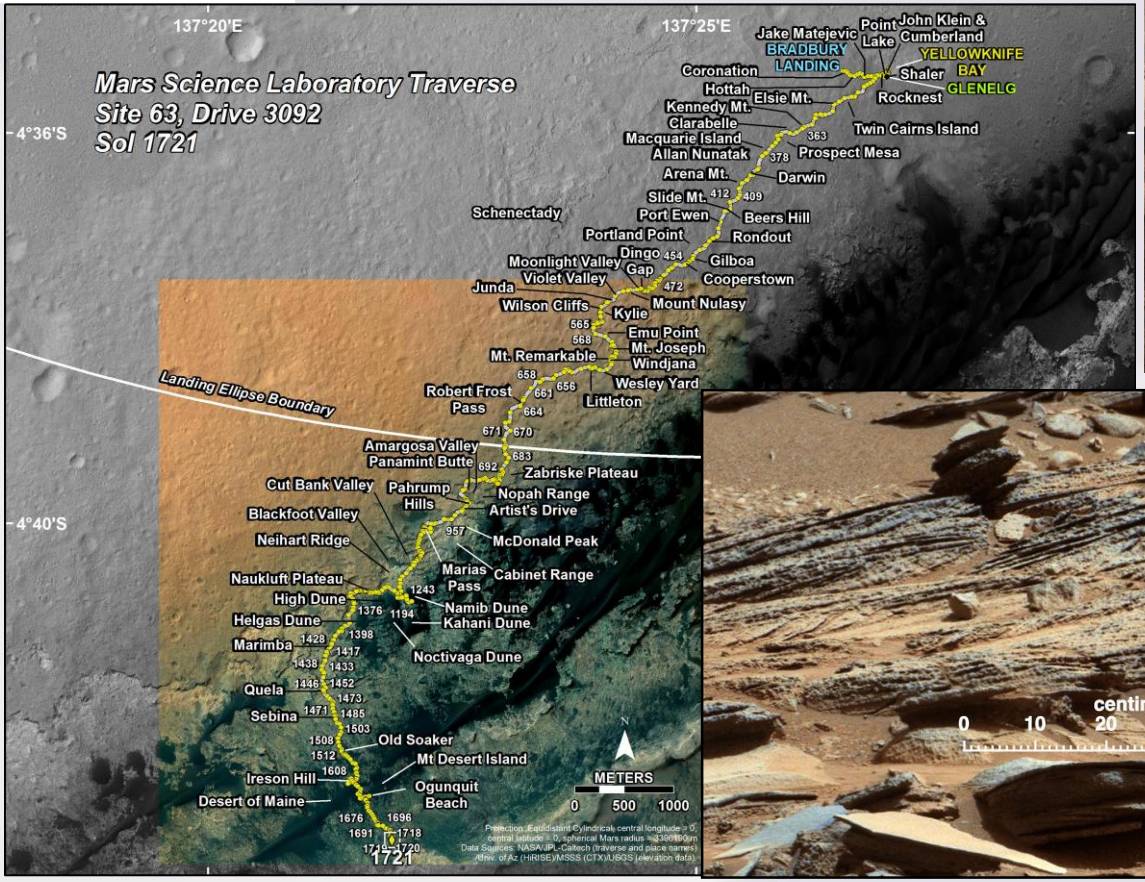
Consistently performing well even in unexplored terrain

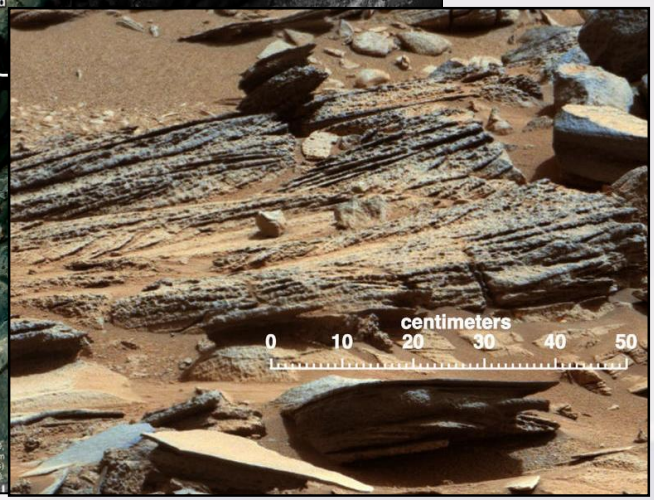




Mars Science Laboratory

Discovering and exploring habitable environments in Gale Crater since 2012



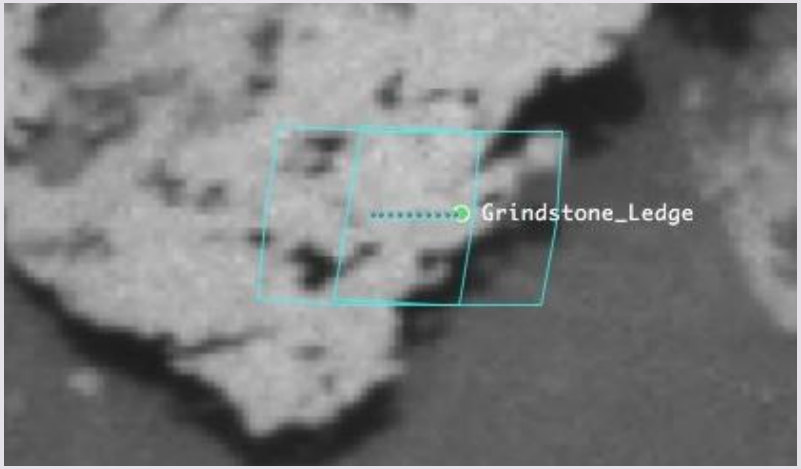


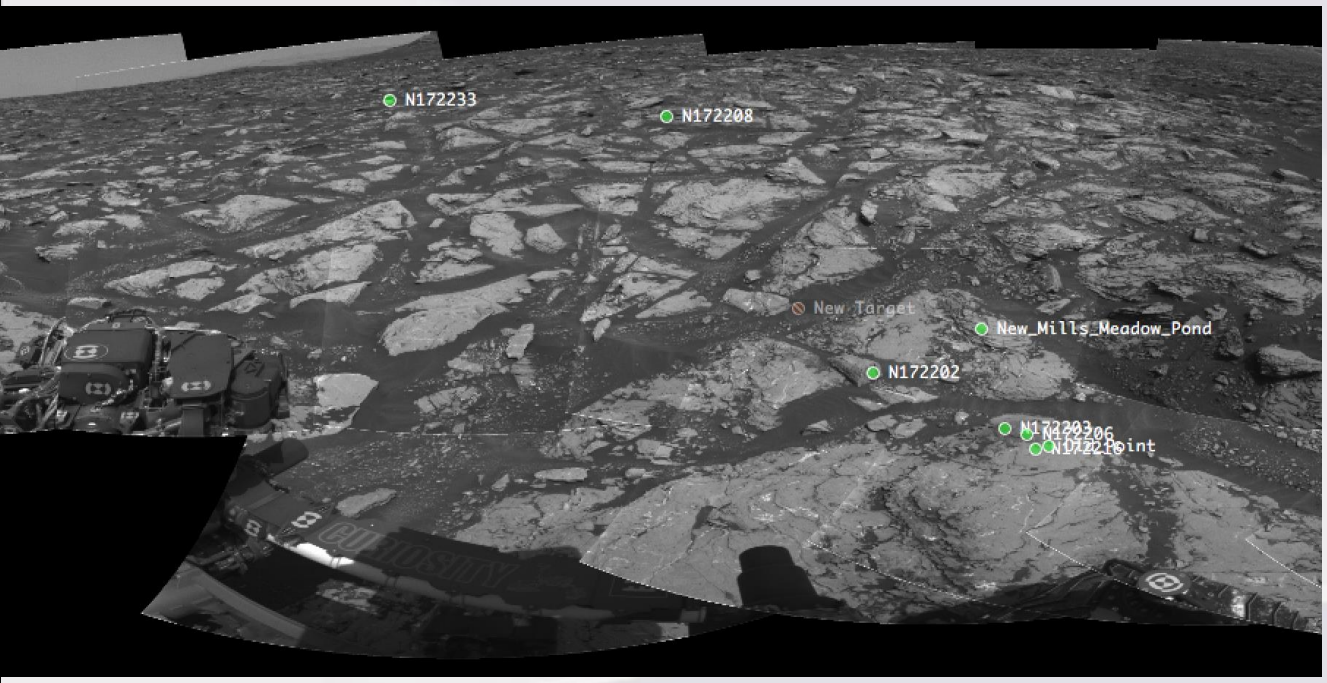
ChemCam Instrument

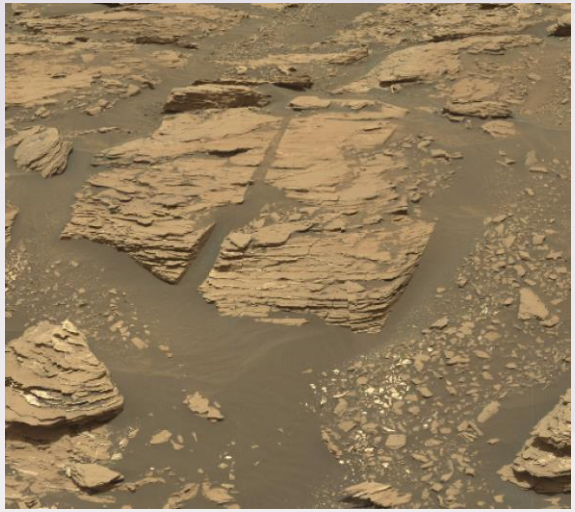
- Laser-Induced Breakdown Spectrometer (LIBS) with Remote Micro-Imager (RMI)
- Gives geochemical composition of rock targets at ranges up to 7 metres
- Over 440,000 measurements on 1500 targets on Mars since 2012
- Joint development of
  - Los Alamos National Laboratory (LANL, Los Alamos)
  - Institut de Recherche en Astrophysique et Planétologie (IRAP, Toulouse)

ChemCam Targeting

- Targets selected by specialists on Earth, inspecting images returned from Mars
- NavCam, sometimes MastCam or MAHLI
- Choose suitable science targets at each location
- Ensure proper focus and raster size/shape



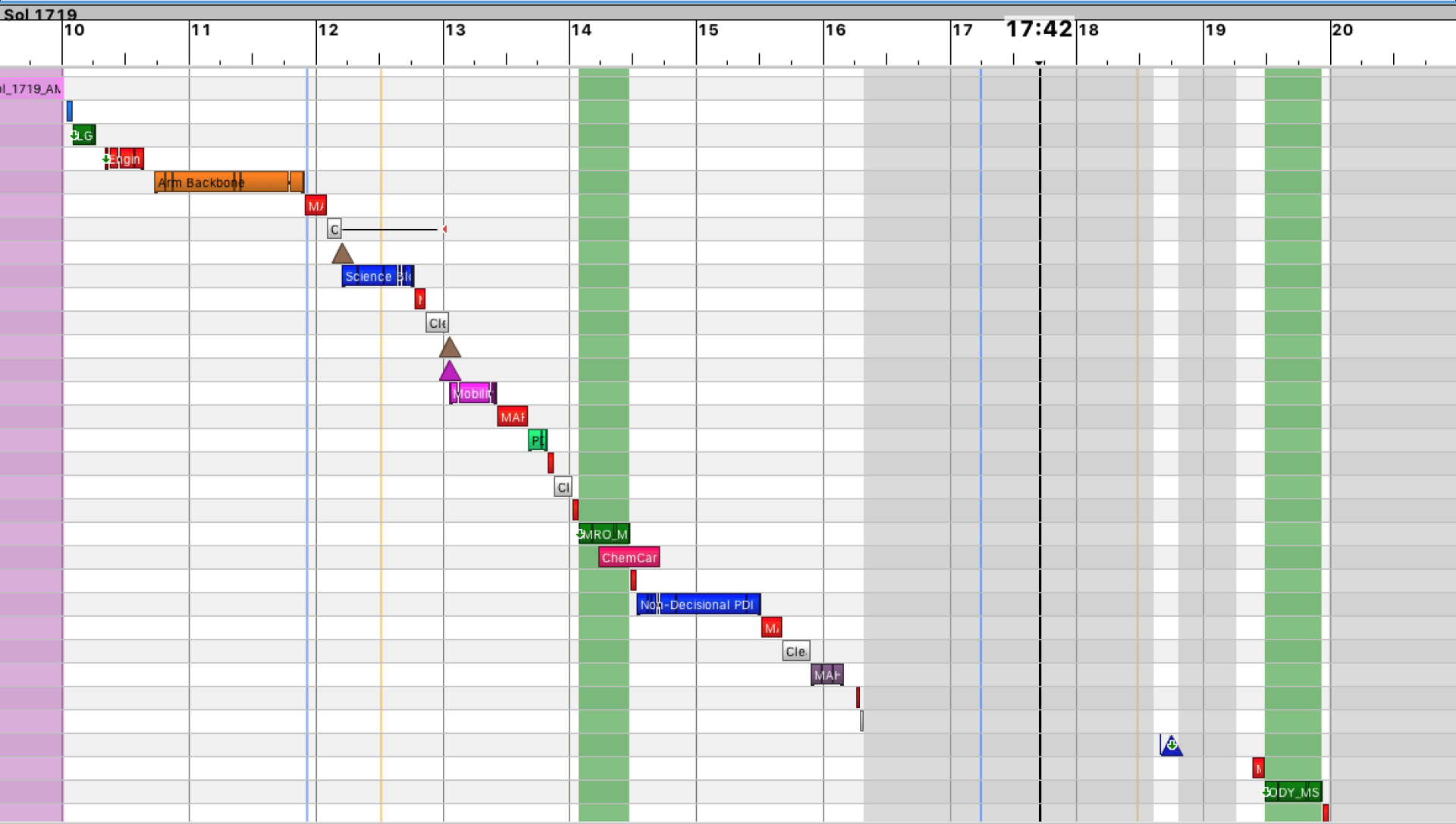




MSL planning

A (simplified) typical day on Mars

Sol 1719: Planned on 6 June 2017



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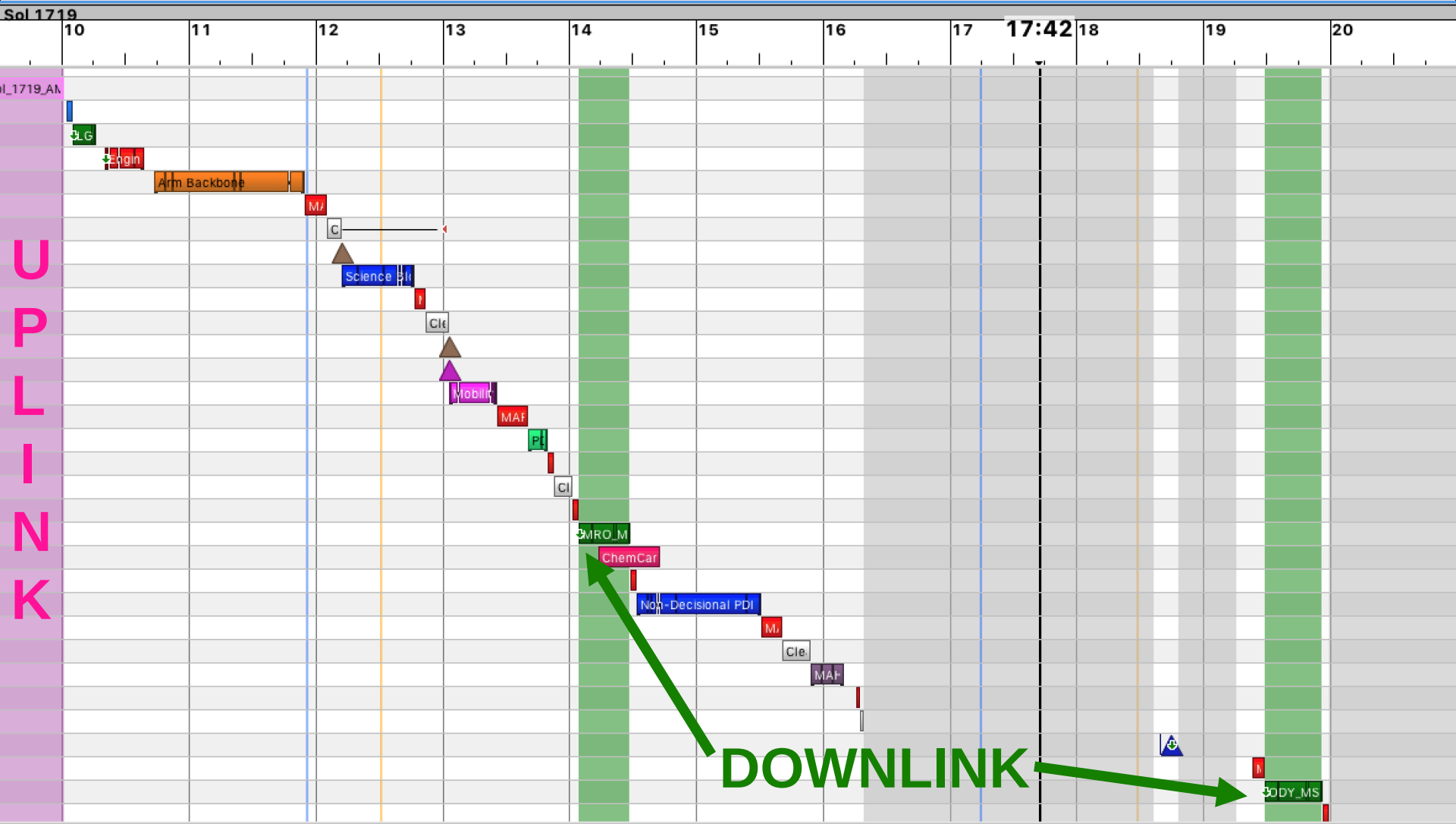

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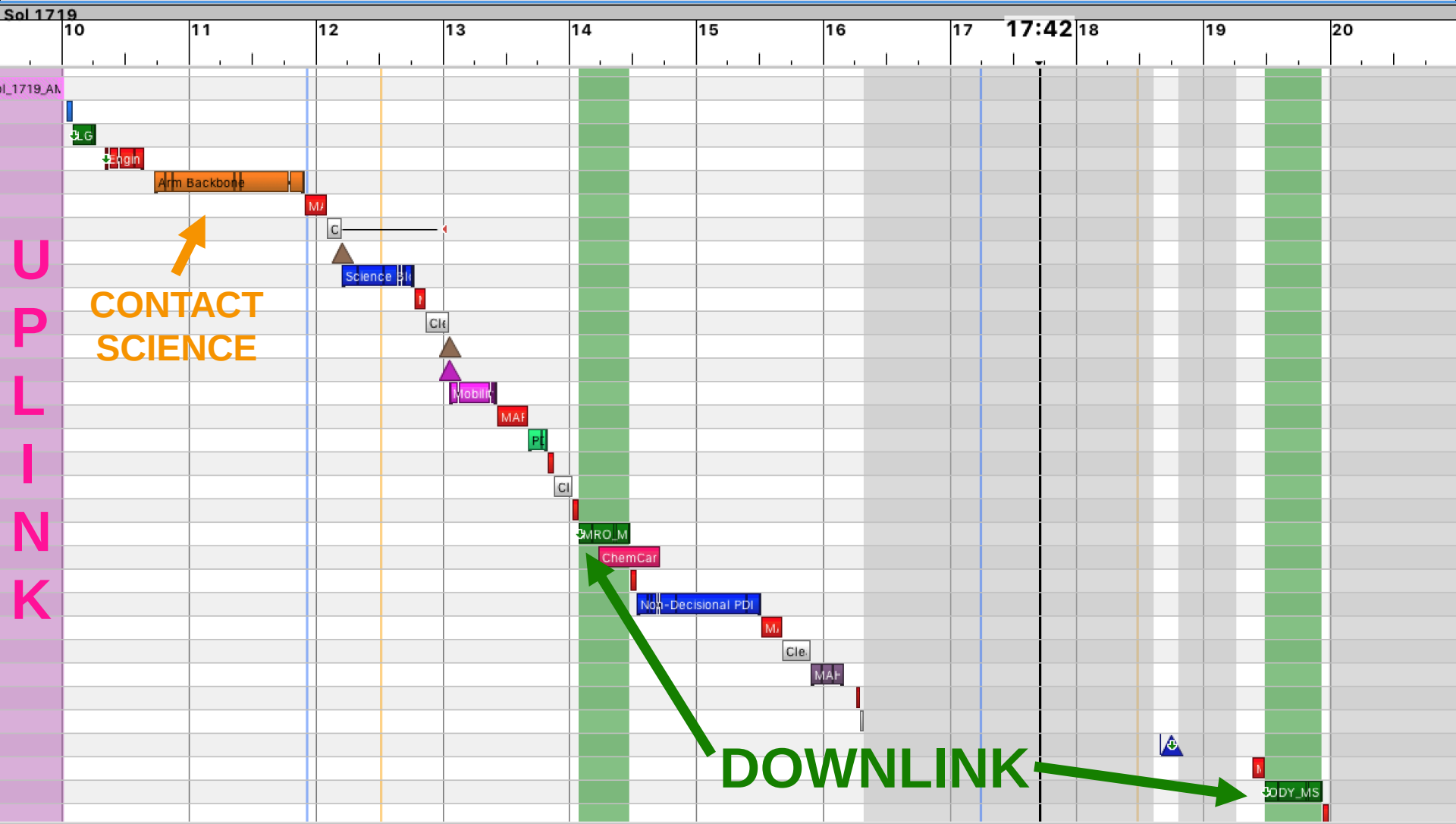

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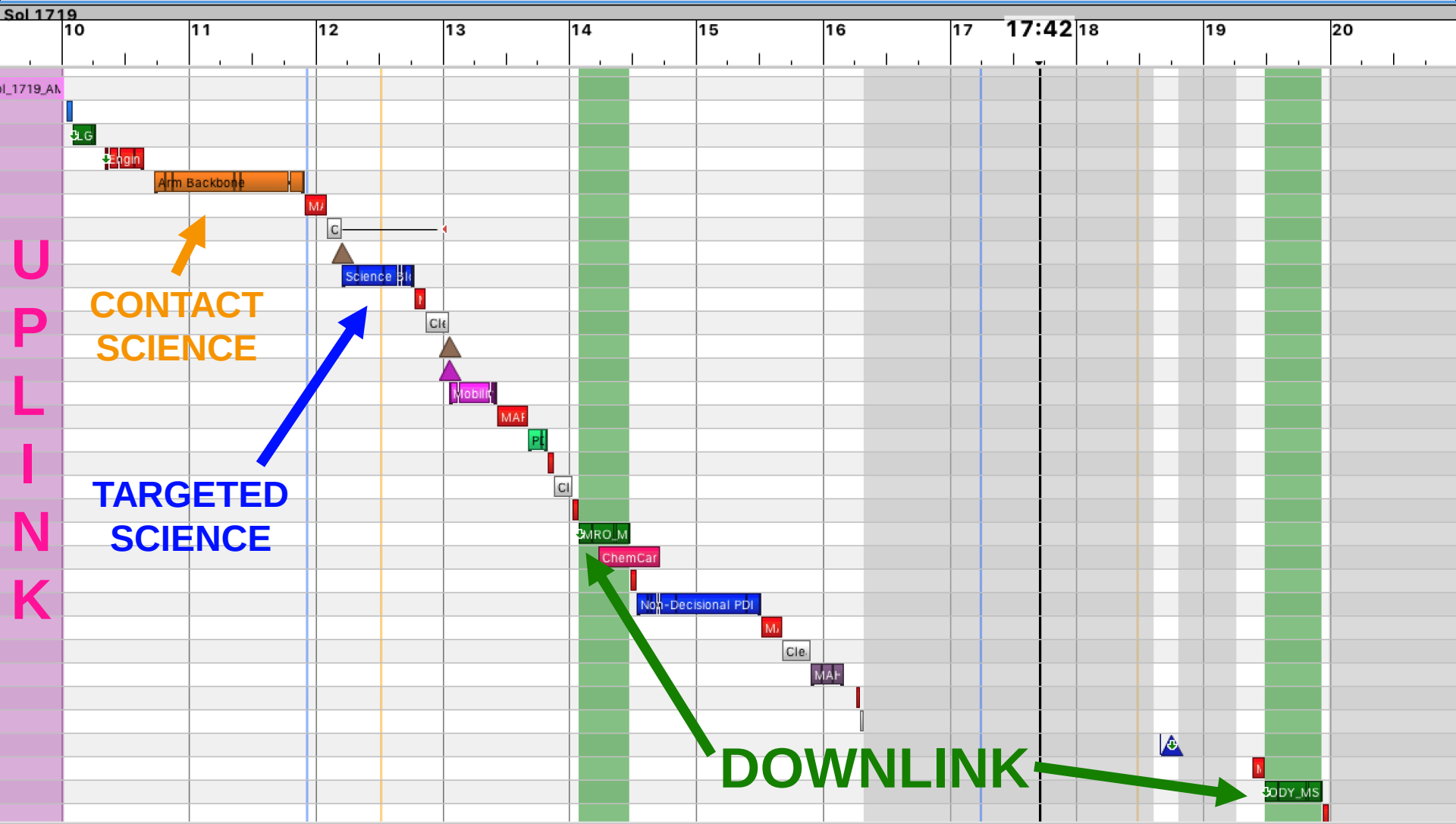

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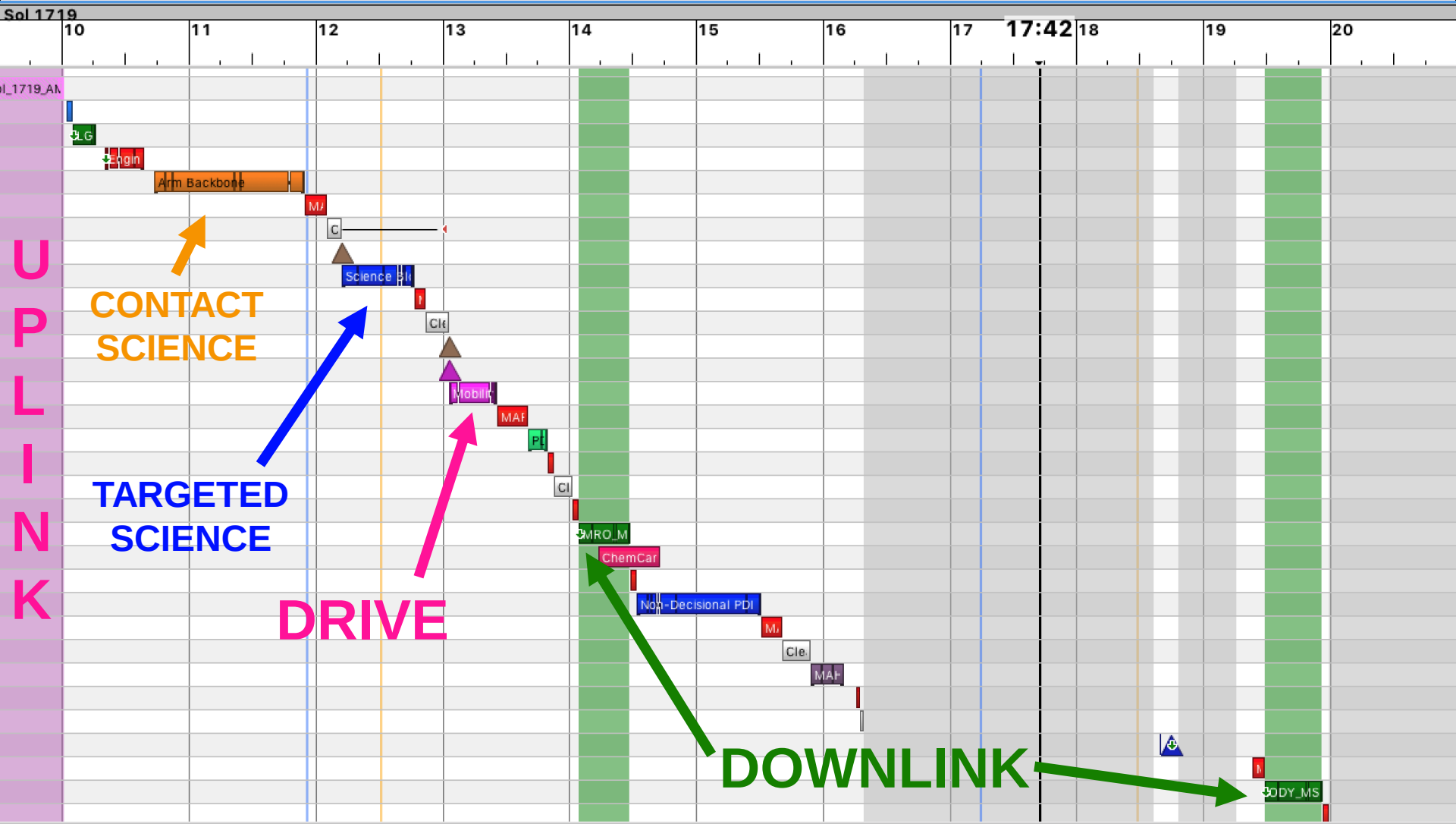

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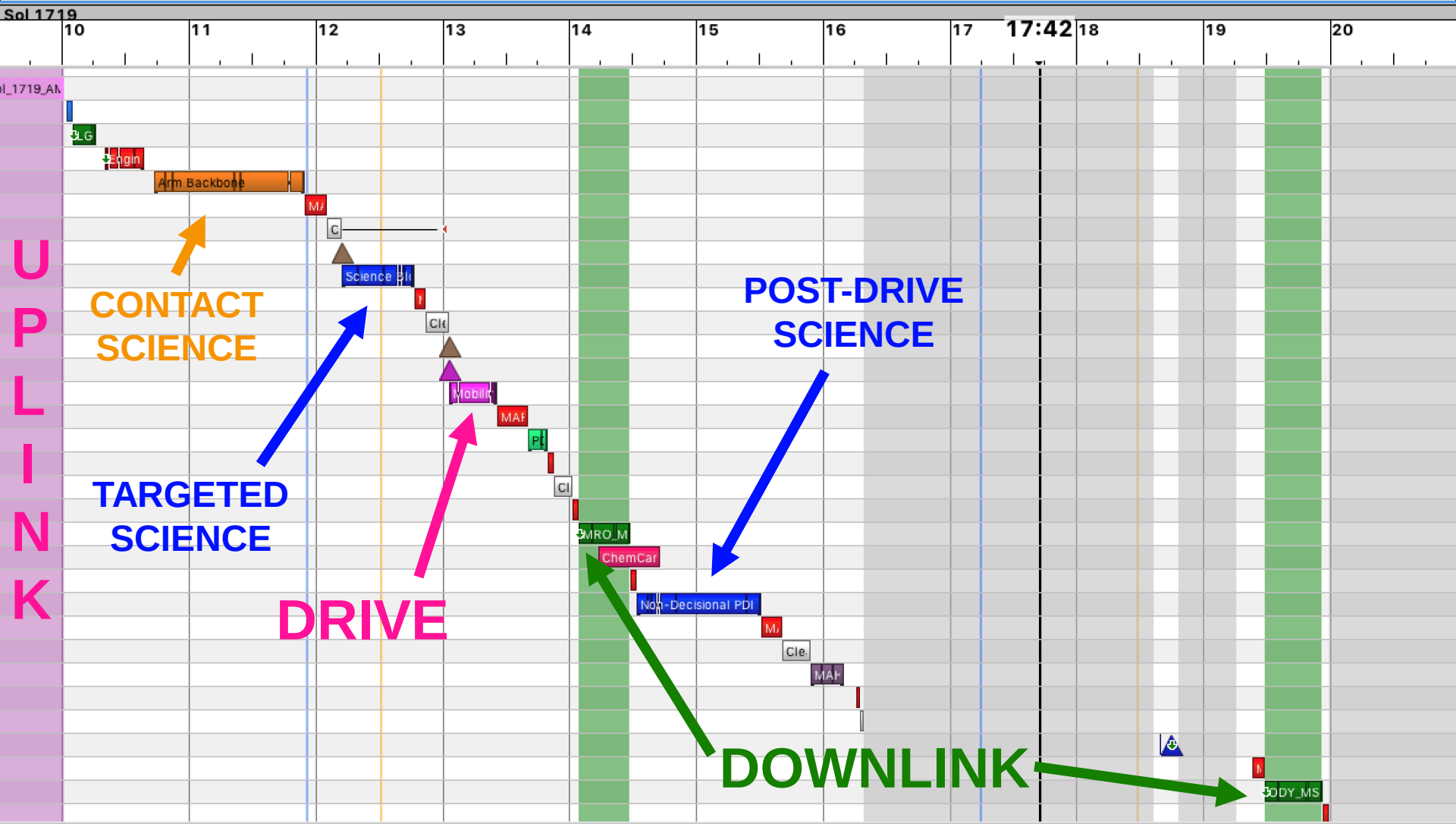

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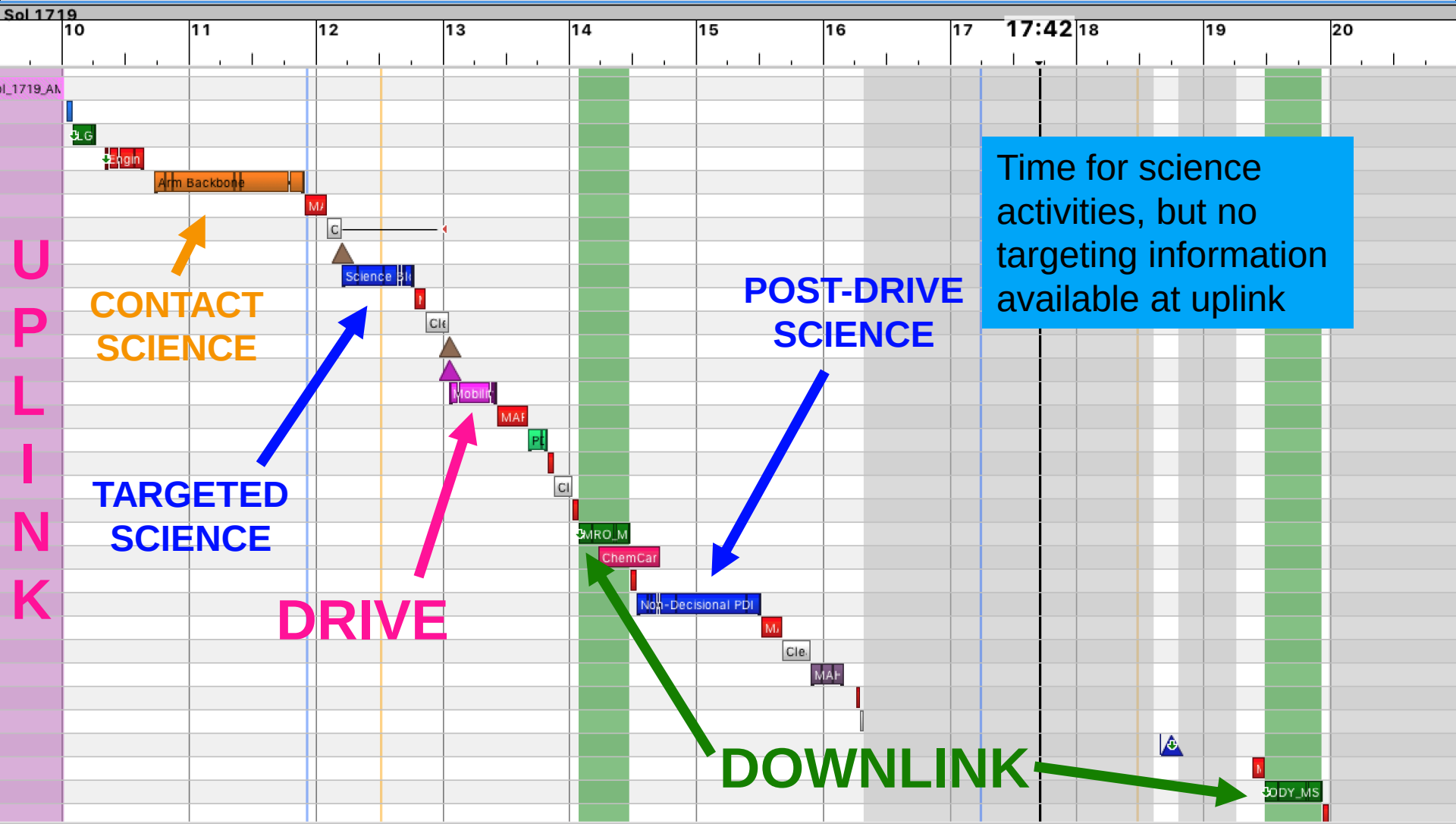

Pointing challenges

Target: White_Cliffs Range: 2.8 m Length: 1.3 cm Width: ~2 mm

Pointing challenges

- Pointing precision is a challenge!
  - Backlash
  - Stereo accuracy & registration
  - Rover shifting/settling
  - Thermal expansion
- Missing targets
  - Try again or lose the target

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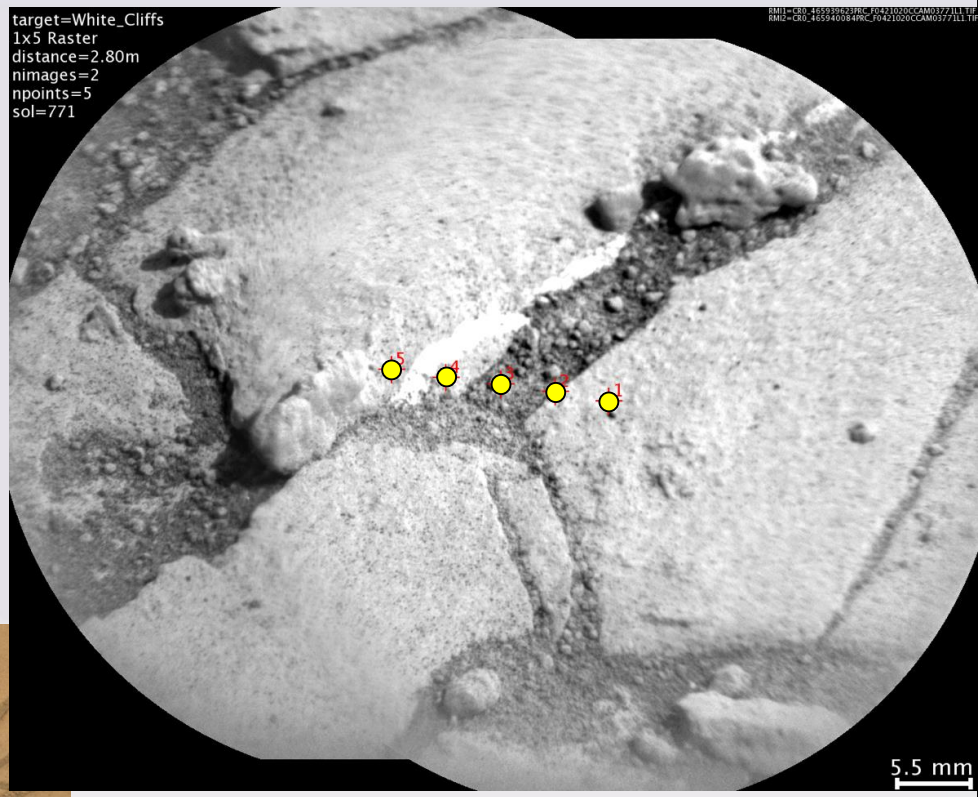

Initial ChemCam raster
1.4 mrad spacing

Pointing challenges

- Pointing precision is a challenge!
  - Backlash
  - Stereo accuracy & registration
  - Rover shifting/settling
  - Thermal expansion
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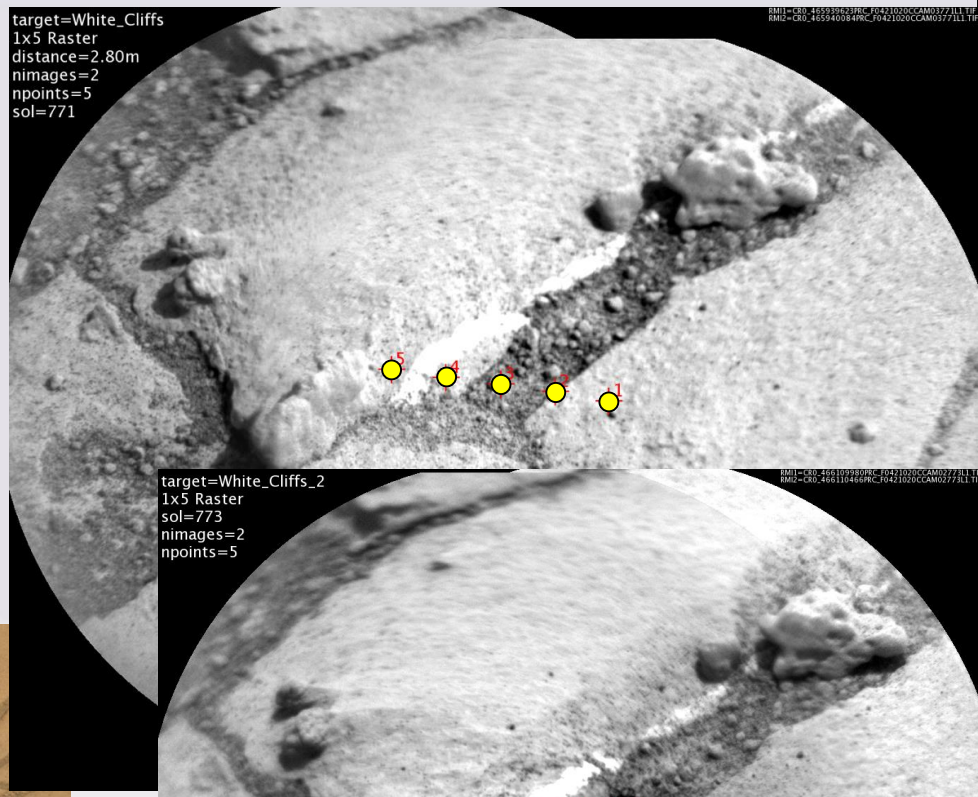


AEGIS Intelligent Targeting System

"Automated Exploration for Gathering Increased Science"

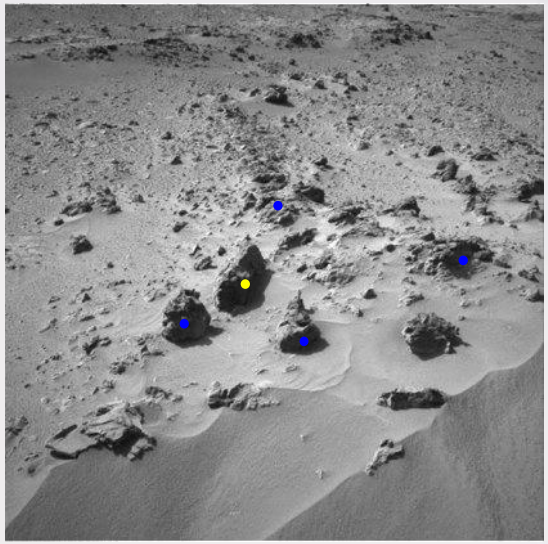
AEGIS was first flown on MER Opportunity in 2010

- Autonomous target selection for PanCam (mid- or post-drive)

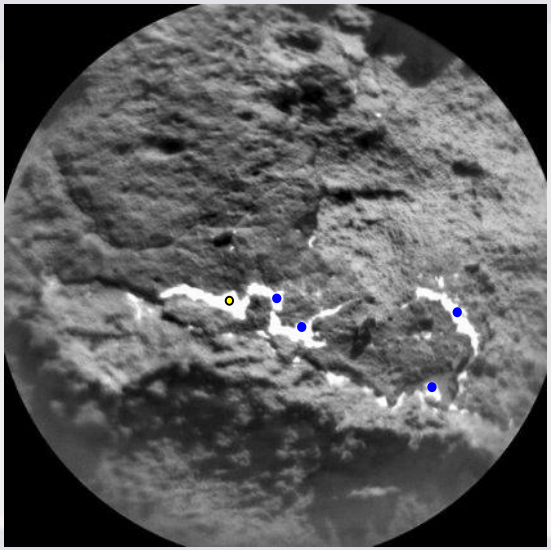
Now in use for ChemCam on MSL, in two roles

- Autonomous target selection in NavCam images
- Autonomous pointing refinement in RMI images

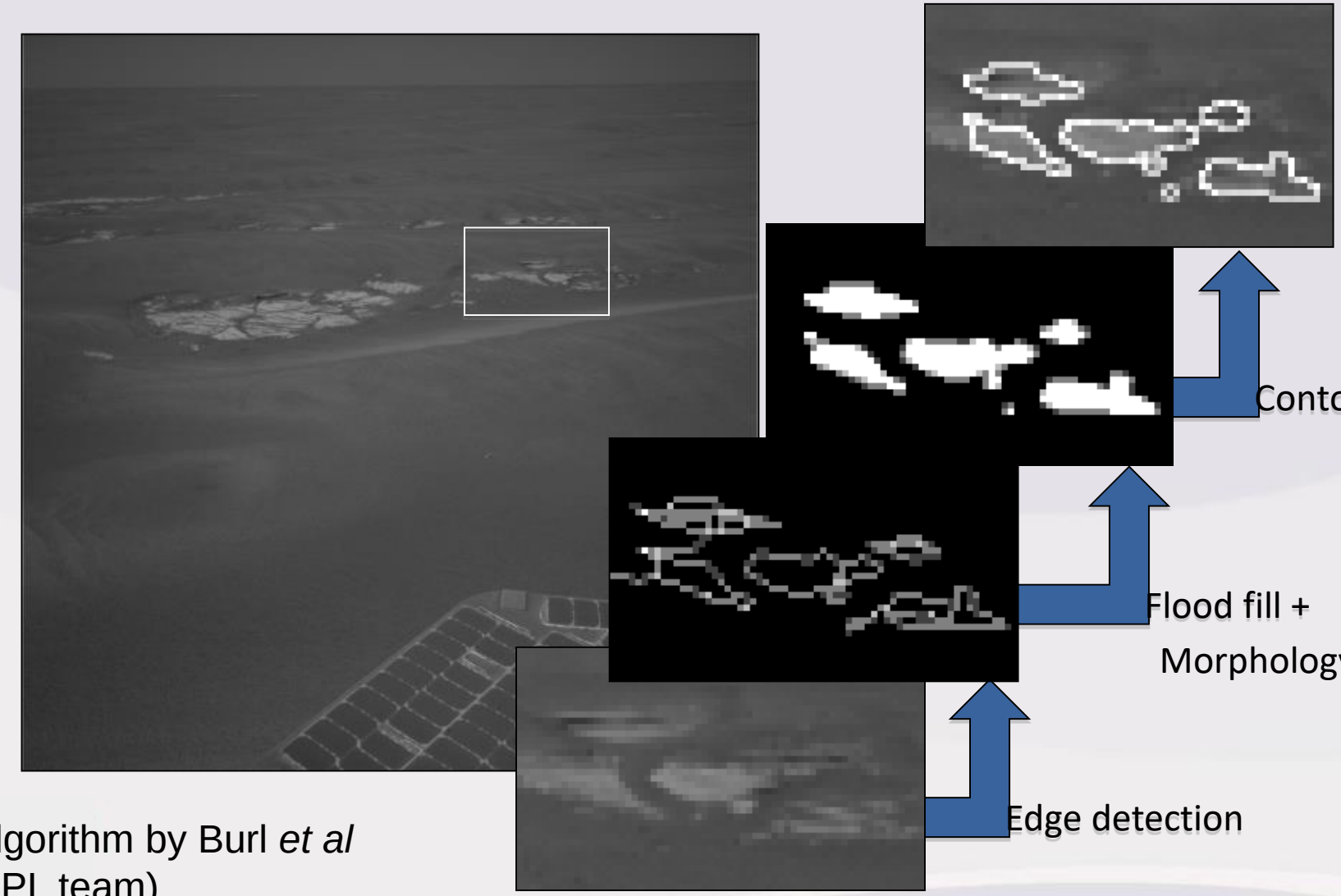
NavCam



RMI



AEGIS Target Detection using Rockster

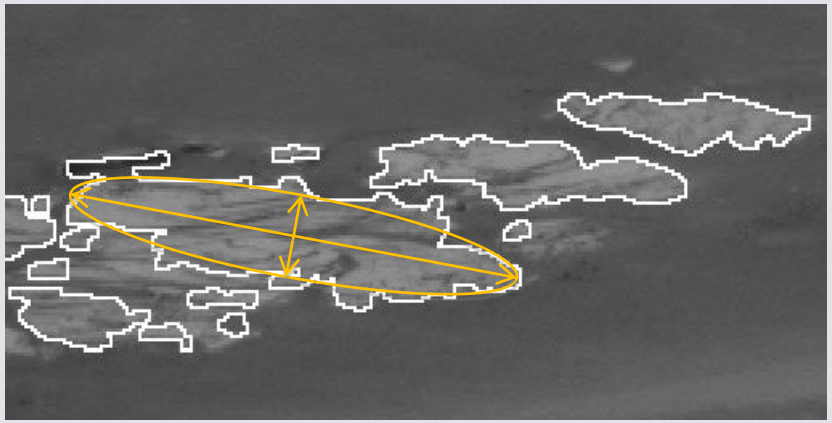


Algorithm by Burl *et al*
(JPL team)

Target Property Evaluation

Size

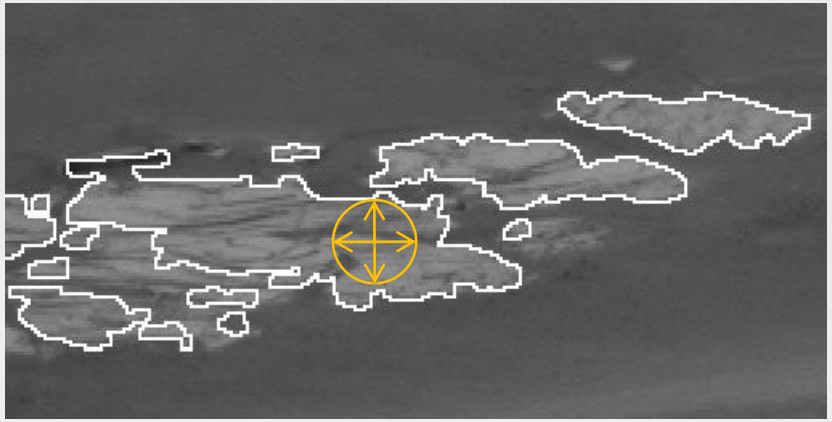
- Number of pixels
- 3D estimate (from stereo)
- Ellipse semi-major axis
- Ellipse semi-minor axis



Ellipse fit example

Position

- Distance from rover
- Inscribed circle x, y
- Site x, y, z
- Site az, el



Inscribed circle example

Target Property Evaluation

Intensity

- Mean
- Variance

Light Dark

Shape

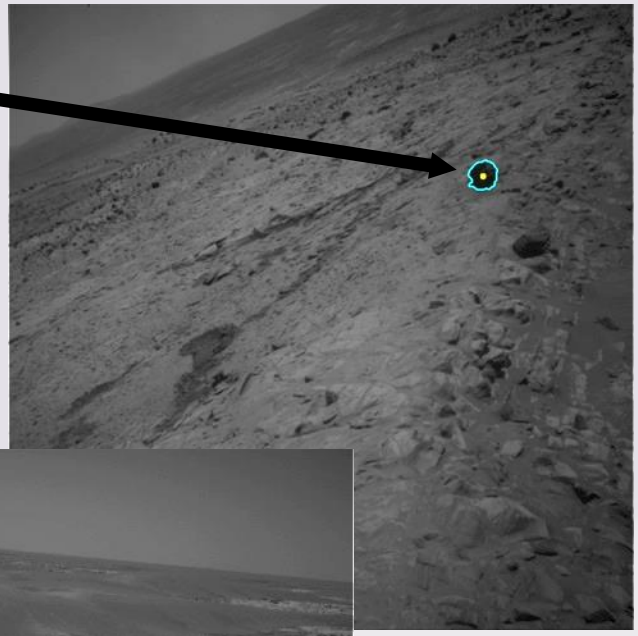
- Eccentricity
- Ellipse fit error
- Ruggedness
- Orientation

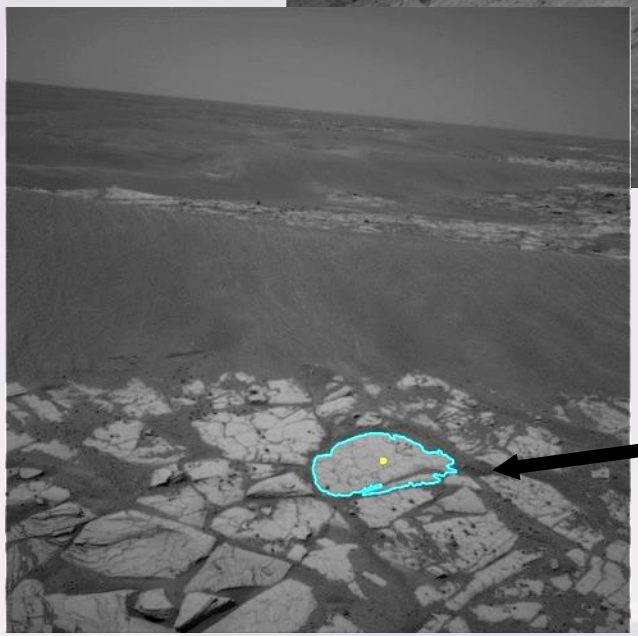
Rounded Angular

Target Prioritization

- Scientists can prioritize different property values
  - Single or combinations
  - e.g., prefer large, high albedo rocks
- Property setting is done at command sequencing
- Can be easily changed as rover enters different terrain areas
- Can support specific mission campaigns
  - E.g. cobble finder, outcrop finder

Detected rock of round shape





Detected rock of large size

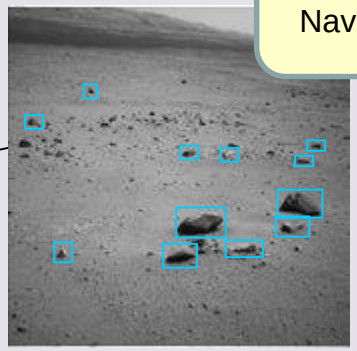
Onboard Process

Image pointing determined by ground.

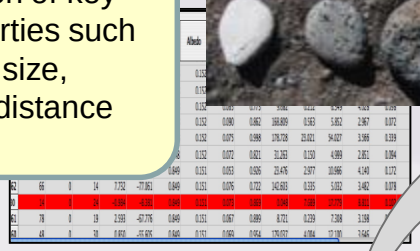
Navcam or RMI acquisition

Target detection

Detection of rock candidates in Navcam image.



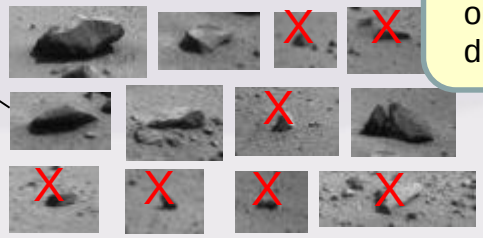
Quantification of key target properties such as intensity, size, shape, and distance from rover.



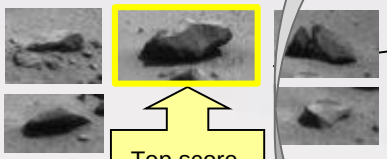
Target feature extraction

Target filtering

Ops can filter targets based on size, distance, etc.



Ops can prioritize important properties for each run



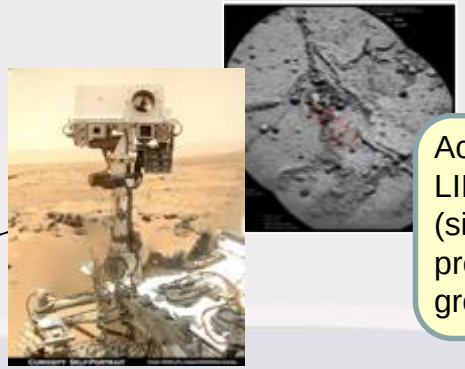
Top score for large size

Target prioritization

Set VTT frame to target position

Can repeat for multiple targets

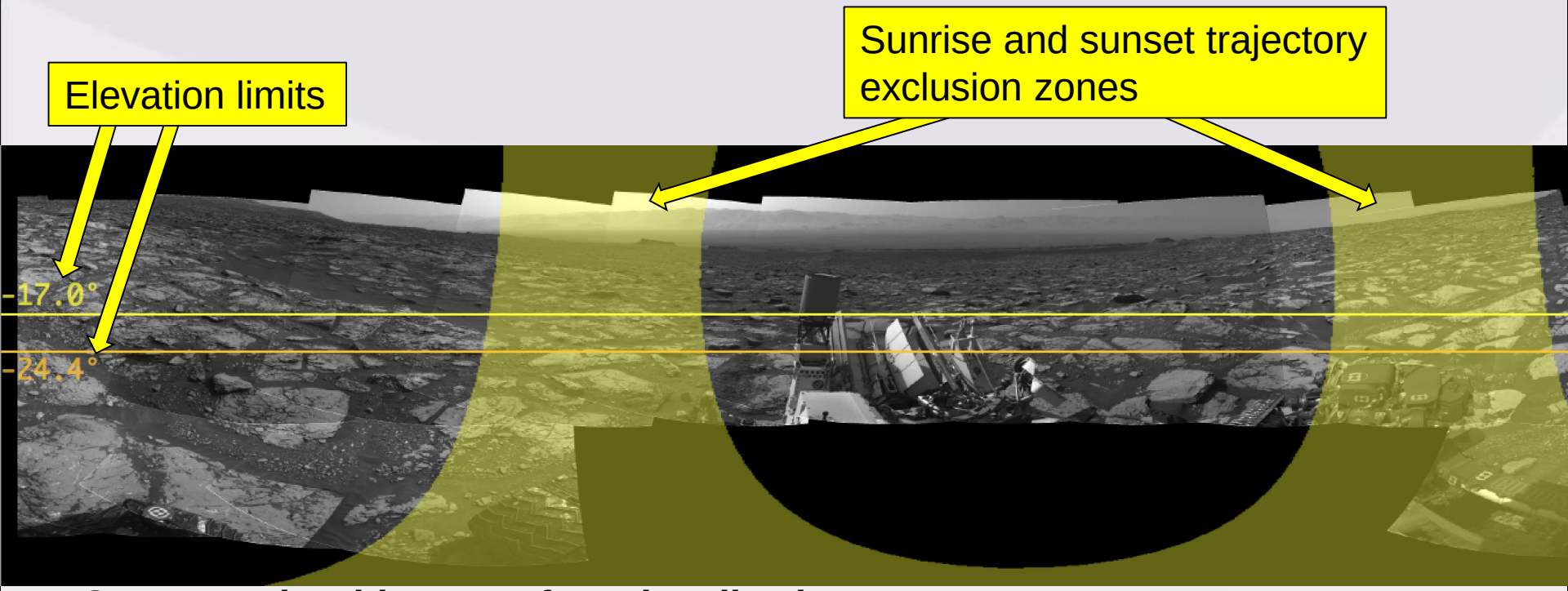
CCAM raster acquired using VTT frame



Acquire ChemCam LIBS raster of target (size and direction pre-specified by ground)

ChemCam Sun Safety

- ChemCam can be damaged by pointing at the sun
- Targets must be in safe pointing zones
- Slews between targets must also protect the instrument
- AEGIS must protect ChemCam

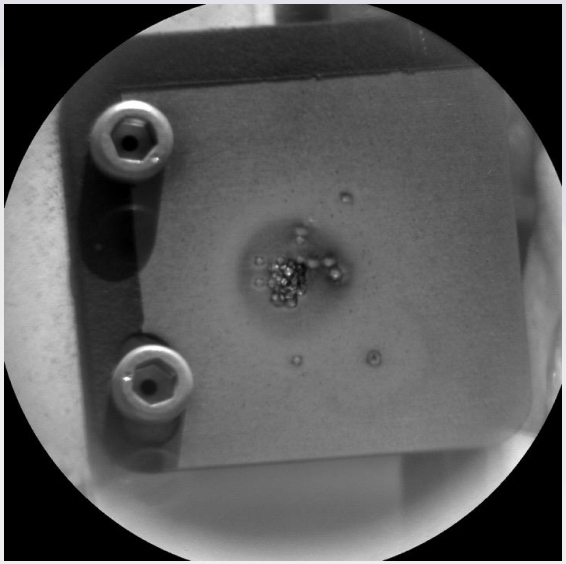


NavCam mosaic with sun-safety visualization

Planners must choose targets which are safely away from the sun.

ChemCam Collision Safety

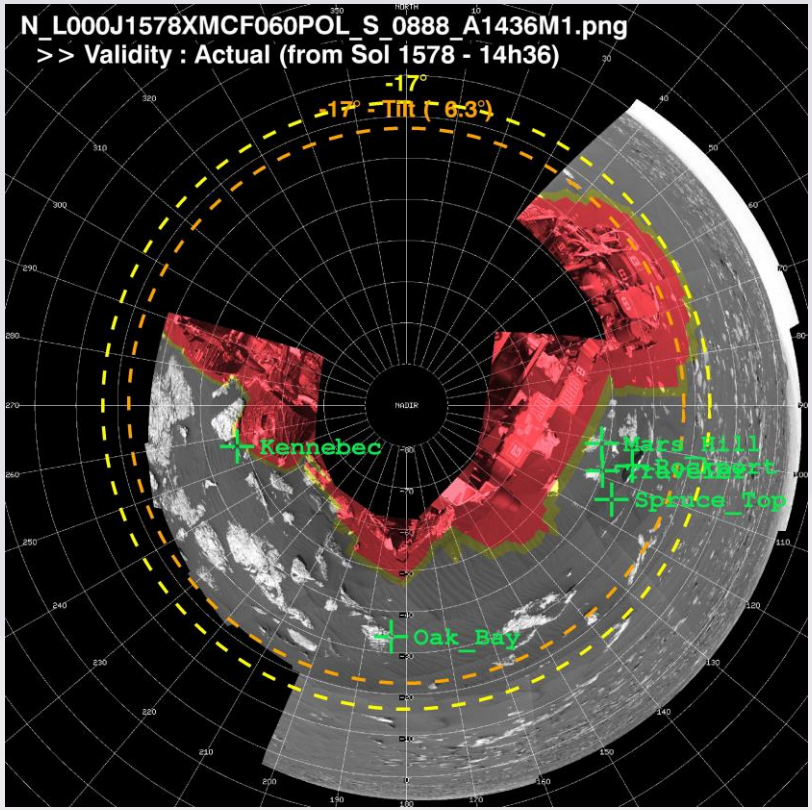
- Don't shoot the rover!
- AEGIS must recognize and reject unsafe pointings
- Onboard model of rover articulation



ChemCam calibration target, sol 1126

This is what happens when ChemCam's powerful laser hits a plate made of solid titanium.

It is important to prevent ChemCam from shooting the rover anywhere but on the calibration target.

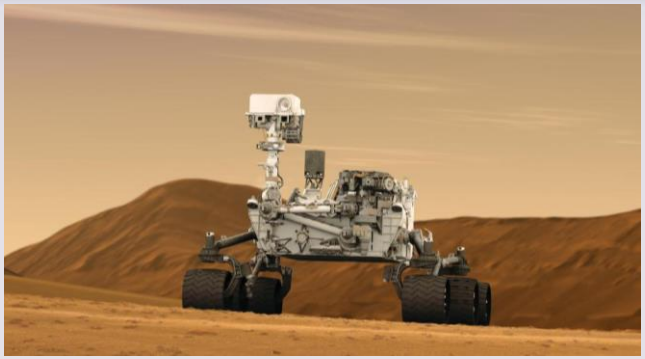


ChemCam collision check graphic

ChemCam PULs model proximity of targets to the rover in angular space. Sometimes, detailed modeling by Rover Planners is needed.

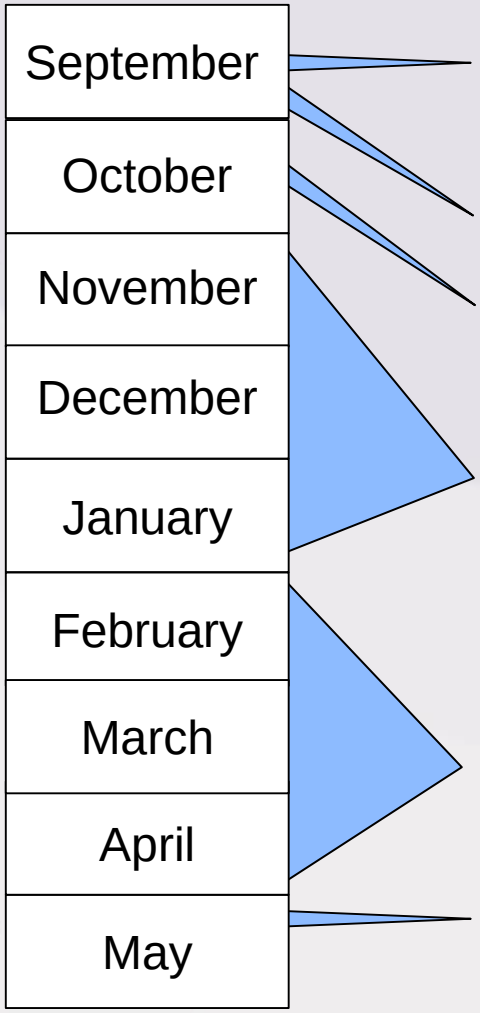
The current NavCam mosaic is plotted in polar co-ordinates; exclusion zone (the rover body) is shaded red and yellow.

MSL Infusion Challenges



- *Curiosity* hardware and software complexity
- New safety constraints compared to MER
  - Sun-Safety
  - Collision
- Limited onboard memory
  - 256 MB of DRAM, 128 MB of RAM – AEGIS limited to 16MB
- Flight processor: RAD750 @ 133 MHz
  - AEGIS runtime: 2-5 minutes
  - Stereo information on targets is time consuming
- First technology to use MSL component load (similar to loading a flight software patch)
  - Navigating a new process for the flight system
- Want to limit operations complexity
  - New commands need to be intuitive for operators to use
  - Telemetry should be easily understandable

Deployment timeline



- AEGIS ChemCam implementation fully tested, verified, and validated 17 Sep 2015
- AEGIS software uploaded to MSL 29 Sep 2015
- AEGIS software installed to MSL flight software 10 Oct 2015
- 7-step progressive checkout process
  - Nov 2015 – Jan 2016
  - Piecewise in between ongoing science mission activities
- Science and Ops team training, tools update: Feb – Apr 2016
- AEGIS approved for routine science team use May 2016

Use by the Science Team

- After a year of use, has AEGIS proven worthwhile?
- Assessing AEGIS as a tool for science & exploration:
    1. Does it run safely and as expected?
    2. Does it get us ChemCam observations?
    3. Does it get us ChemCam observations *on the kinds of targets we want*?
    4. Is it usable/useful for the team?

Fundamentals

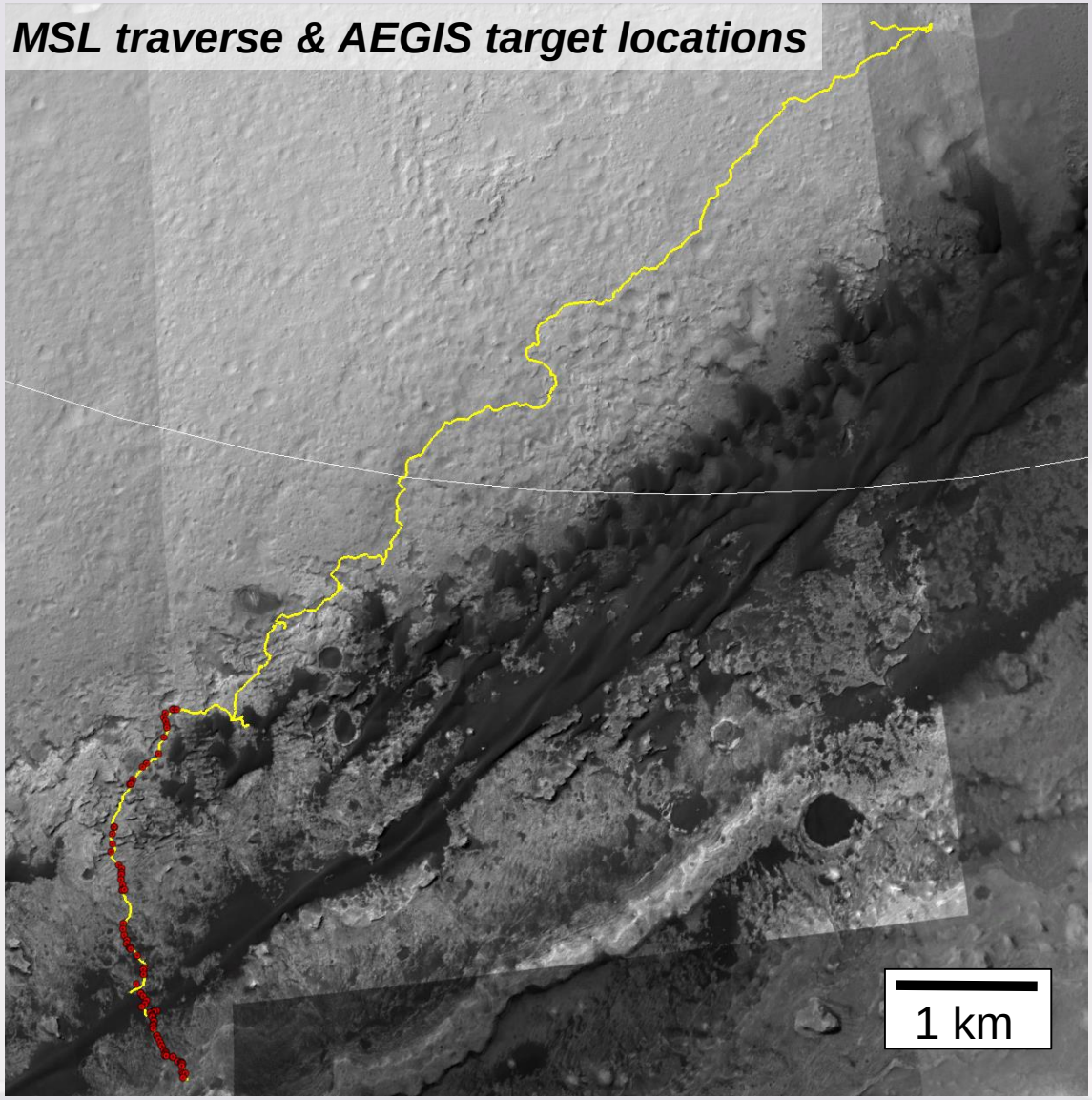
In 90 runs on Mars…

- AEGIS has done these every time
  - Successfully analyzed the source image and identified geological targets
  - Chosen the specified number of targets
  - Returned a ChemCam RLR observation on chosen target(s)

- AEGIS has never done these
  - Triggered a collision warning
  - Triggered a sun-safety warning
  - Given ChemCam a poor focus seed (could cause bad LIBS/RMI data)

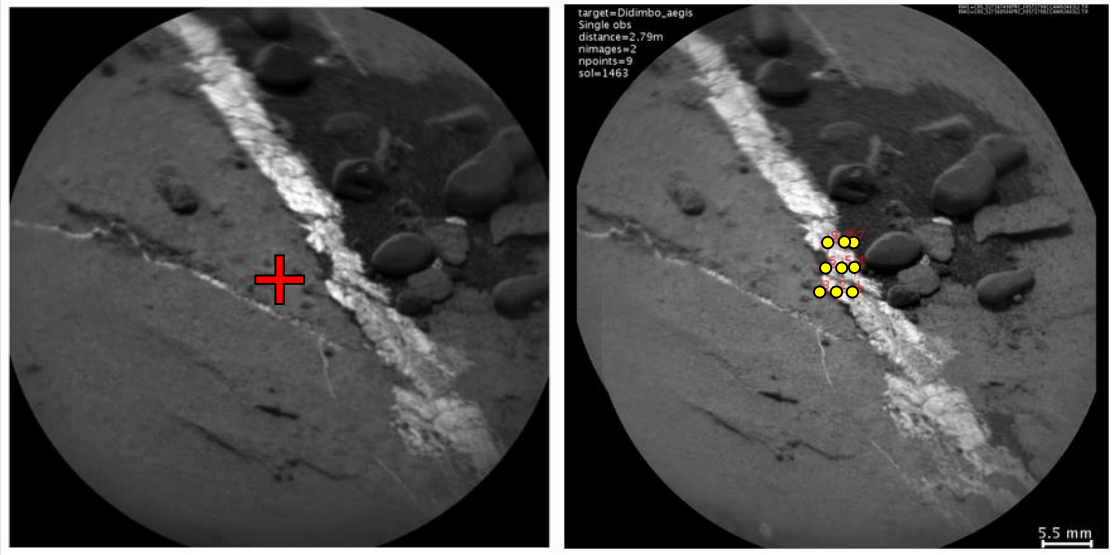
Use by the Science Team

- First used sol 1343
  (planned on 13 May 2016)
- Results here as of sol 1726
  (planned yesterday, 13 June 2017)
- Post-drive NavCam version:
  79 runs, 88 targets
- Pre-drive RMI version:
  2 runs
- Total MSL odometry since rollout: 3.914 km



Results: Pointing refinement

- Sol 1424 & Sol 1463
- Initial (ground-selected) pointing missed target
- AEGIS corrected pointing and hit the target
- Saved the observations – a manual retargeting second attempt would have been necessary. Not possible if rover were to drive in that plan



ChemCam target Didimbo, sol 1463

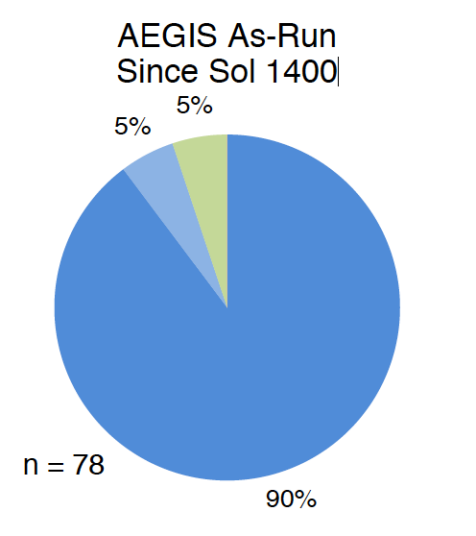
AEGIS corrected a ~3 mrad pointing error, achieving the desired LIBS measurement of the vein.

RMI FOV diameter: 20 mrad
Target profile: Bright vein features
Distance: 2.79 m

Results: Target selection

For the post-drive targets…

- ChemCam hits AEGIS' top-ranked target (or top 2 if time allows) with 3x3 grid of LIBS shots
- Hits clean outcrop 90% of runs since sol 1400 parameter update



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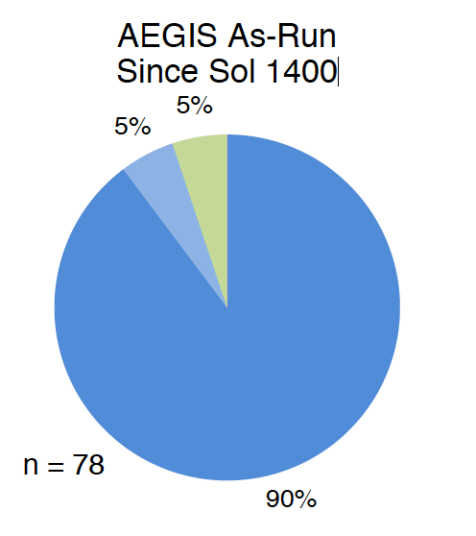

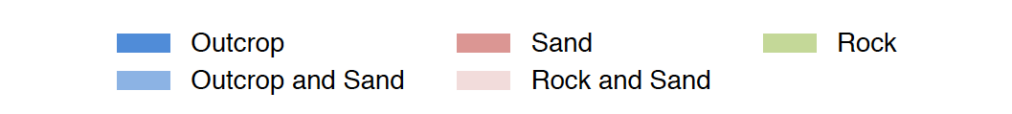

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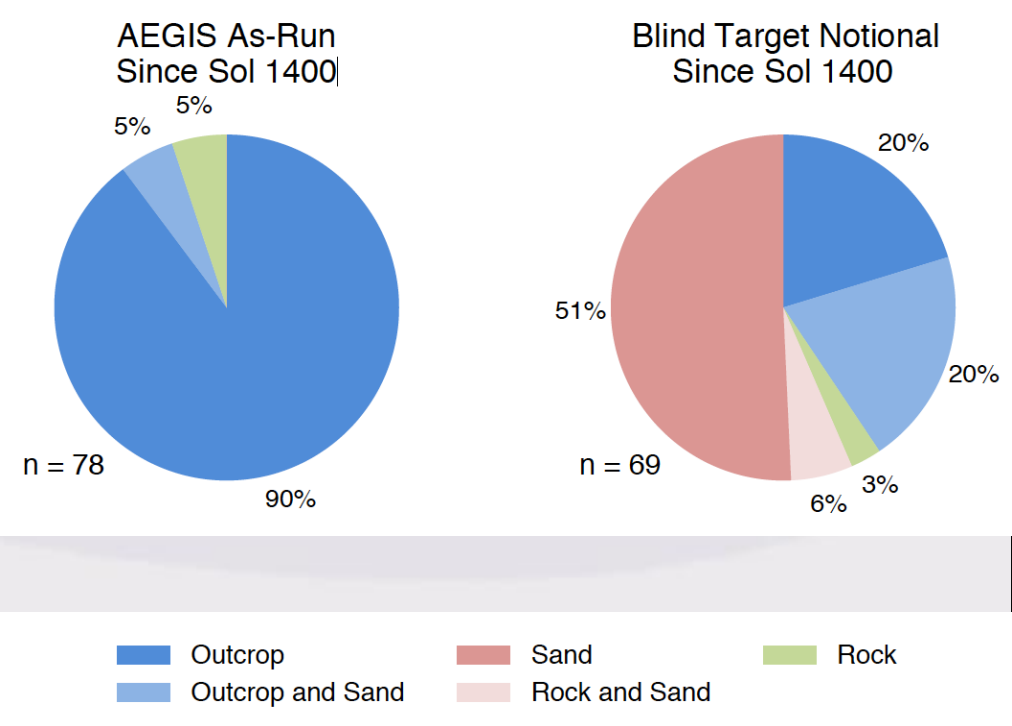
  - Chose desired outcrop unit, but some shots hit sand on top or beside the outcrop
  - Chose a float rock instead of outcrop (usually when there is little outcrop in view)
- Modeled Blind Targeting results for same sols:
  - 10x1 RLR @ standard pointing
  - Only one target



Results: Target selection

Examples from the NavCam runs on the following slides…

- Legend
  - Top target coloured in **green**
  - 2nd-ranked target coloured **orange** if observed
  - Targets retained after filtering: **red** outline
  - Targets found but filtered out: **blue** outline
    - Poor stereo range estimate, sun-safety, collision, outside ChemCam range, very small, very large

Results: Target selection

Examples from the NavCam runs on the following slides…

- Legend
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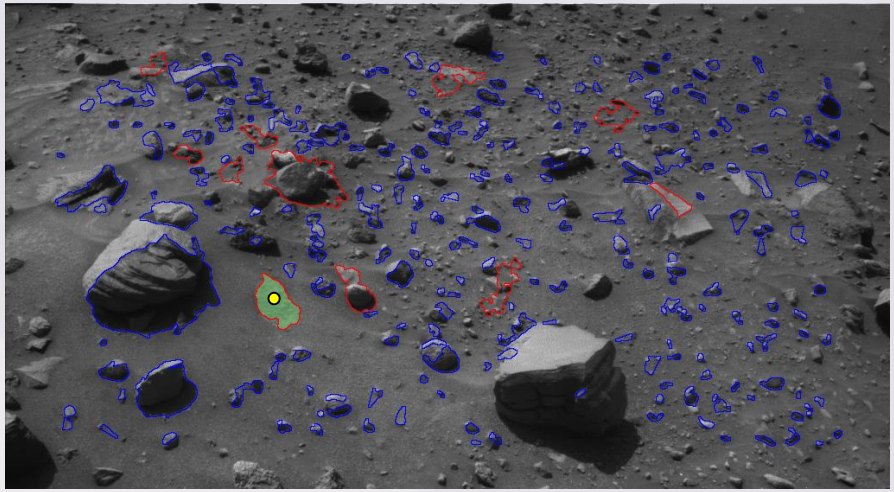
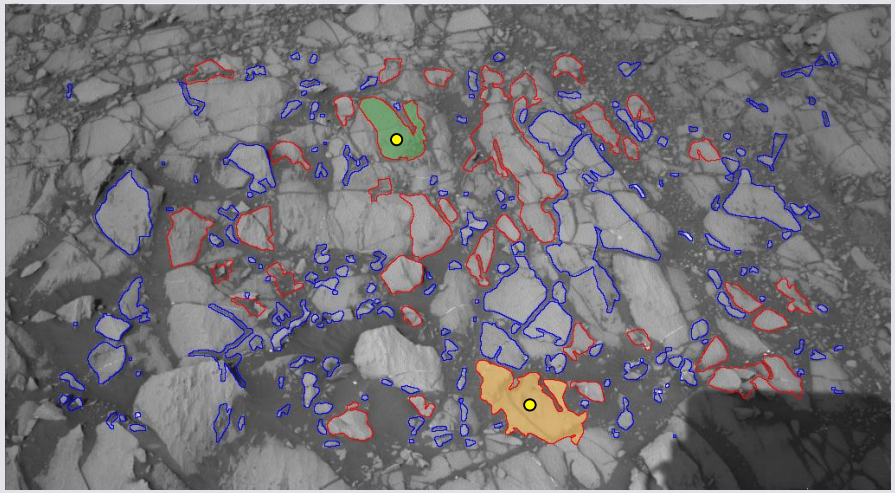
  - Targets found but filtered out: **blue** outline
    - Poor stereo range estimate, sun-safety, collision, outside ChemCam range, very small, very large
- **Keep in mind**
  - AEGIS' target-finding algorithm is searching for closed contours
  - Targets near the edge of the image are rejected for safety reasons
  - **What matters most is**:
    - Which target was picked?
    - Where did the LIBS shots end up?

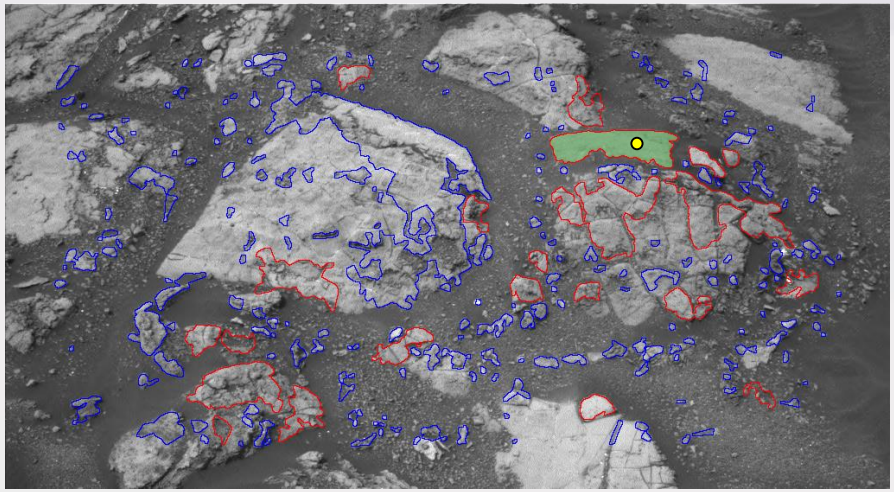
Results: Target selection



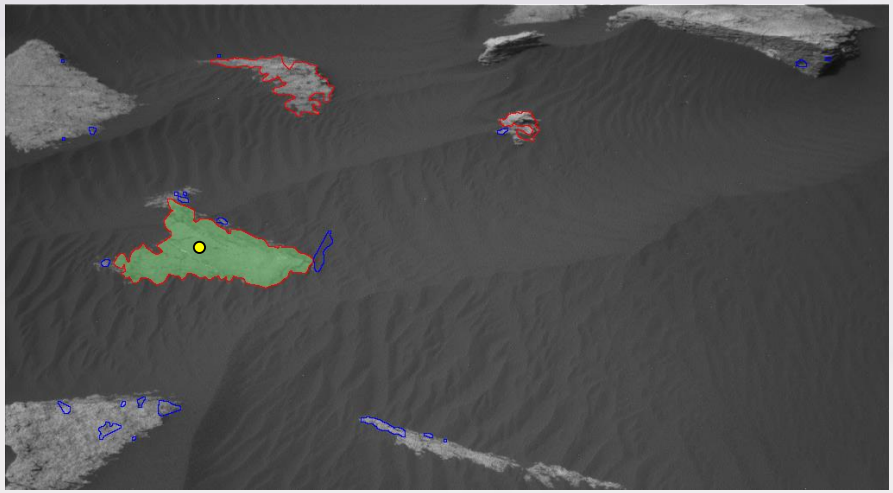
Sol 1400



Sol 1417

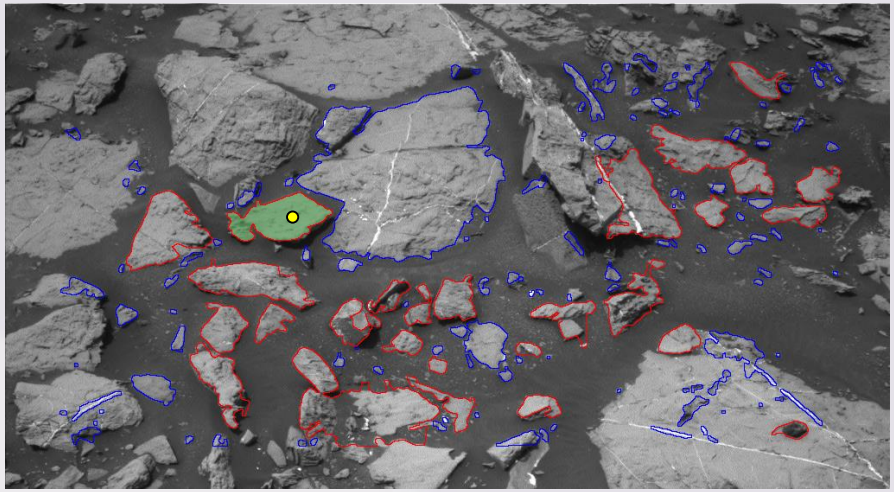


Sol 1481

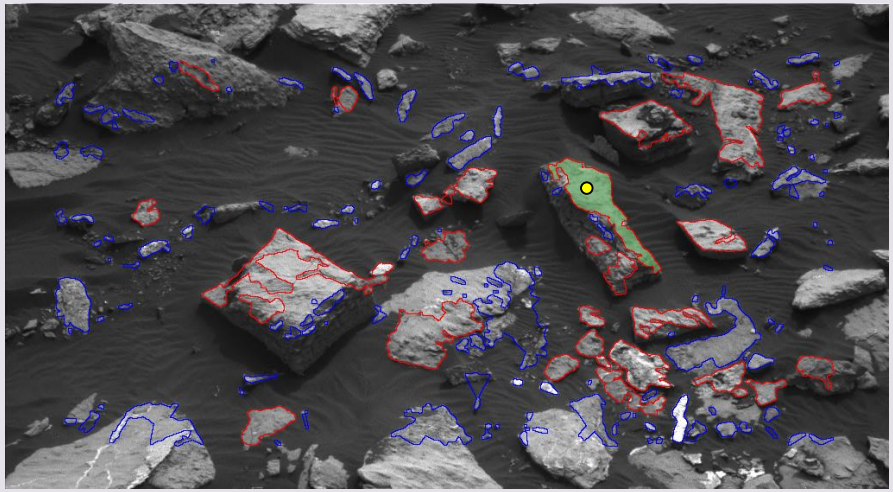


Sol 1636

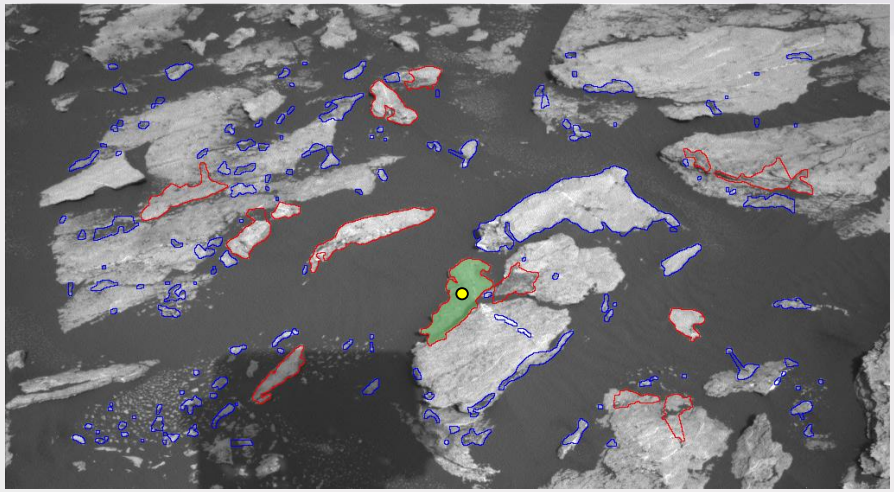
Results: Target selection



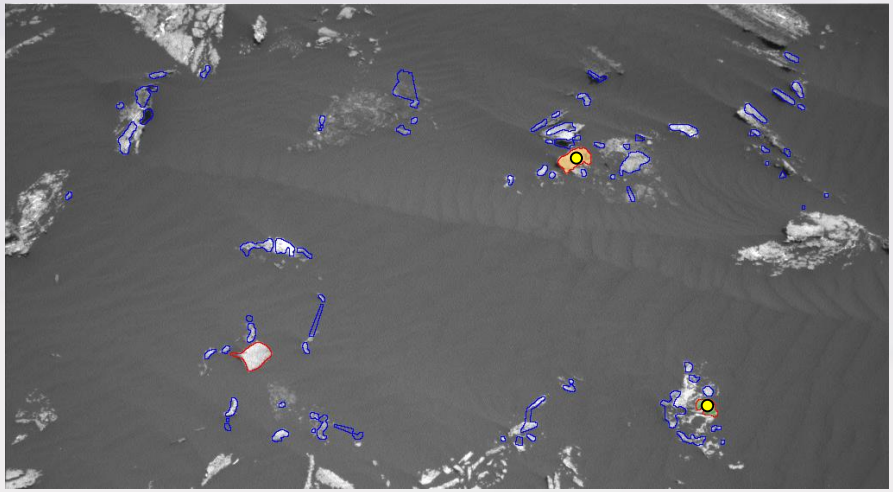
Sol 1449



Sol 1516



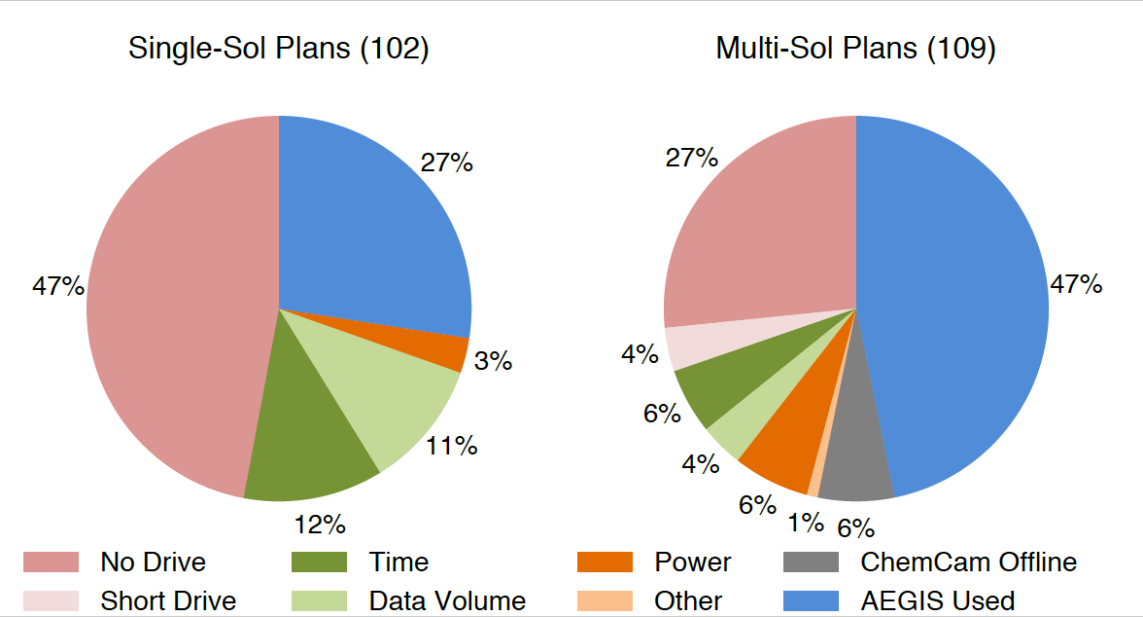
Sol 1605



Sol 1660

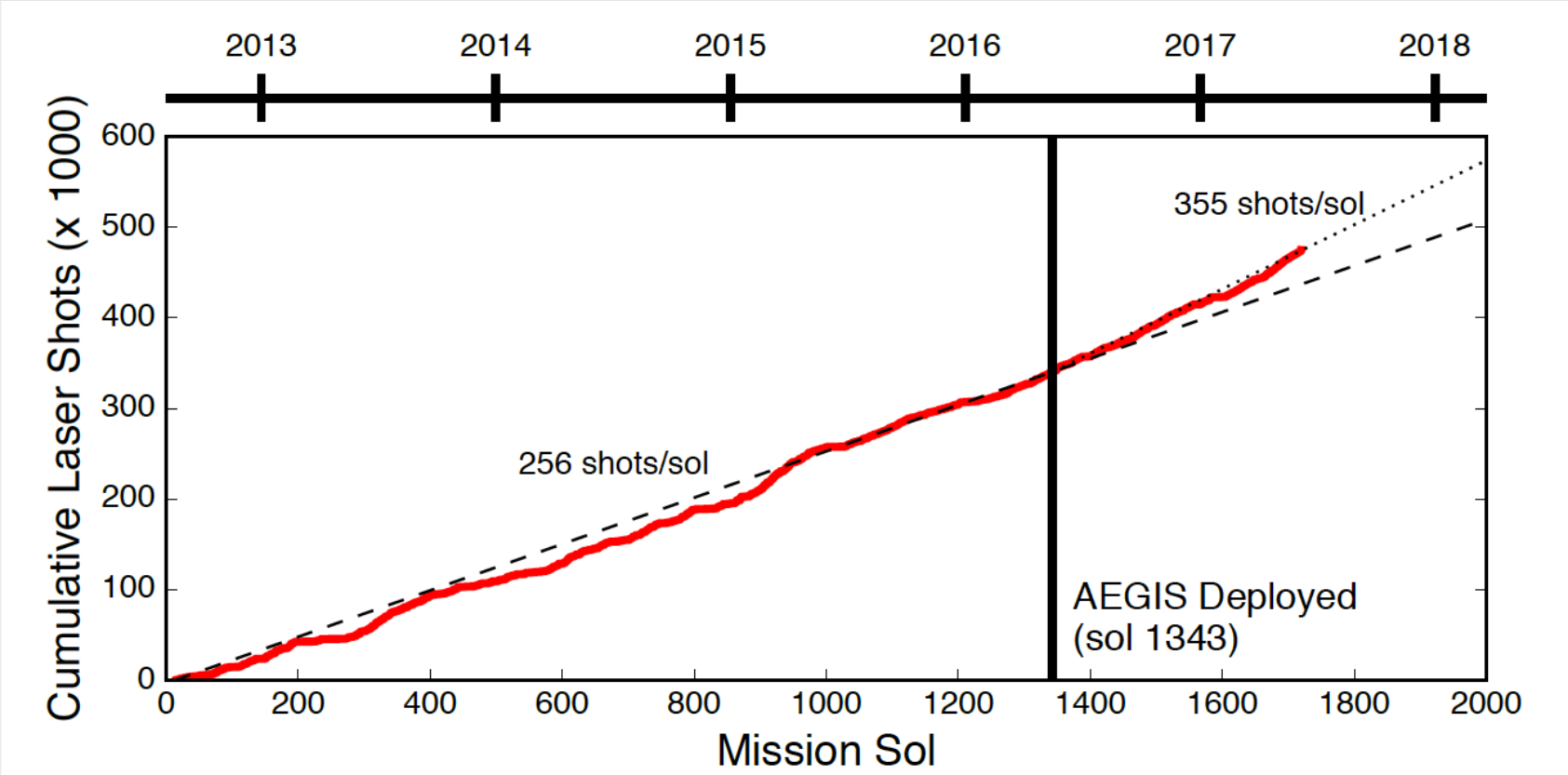
Frequent use

- Charts for **all plans** since sol 1343
  - When AEGIS was used, or why it wasn't



- **When there is a drive**, and ChemCam is available, post-drive AEGIS is used in
  - 61% of all plans
  - 70% of multi-sol plans
  - 50% of single-sol plans

More data from ChemCam



- Significant increase in rate of data return from ChemCam
- AEGIS rollout to science team on sol 1343

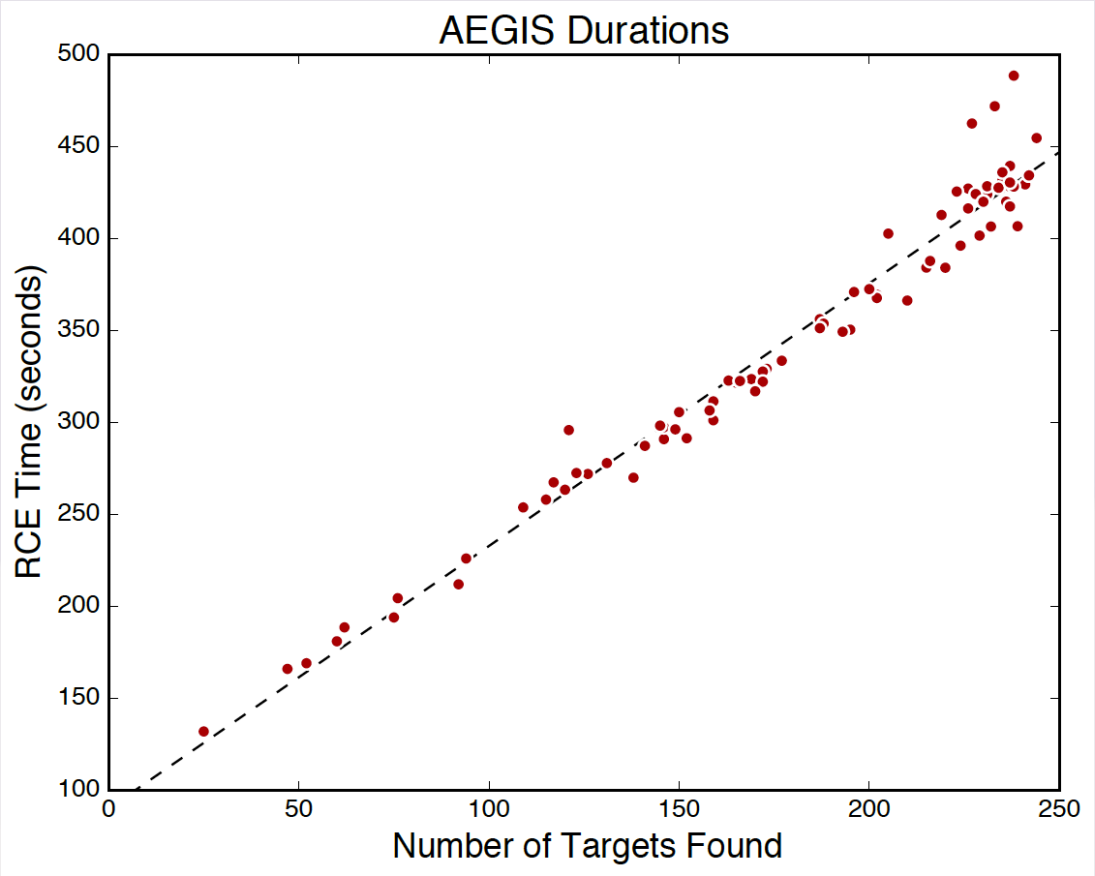
Run durations for NavCam

Run times on MSL flight RCE for `AEGIS_FIND_TARGETS_NAVCAM`

Roughly linear with number of targets found (90 s + 1.4 s per target, R=0.985)

Max duration: 488 seconds

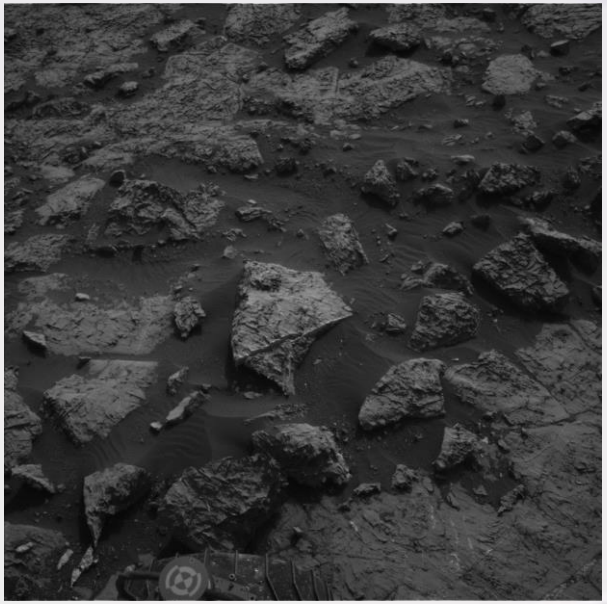
Run times on MSL flight RCE for `AEGIS_FIND_TARGETS_RMI` are about 95-105 seconds

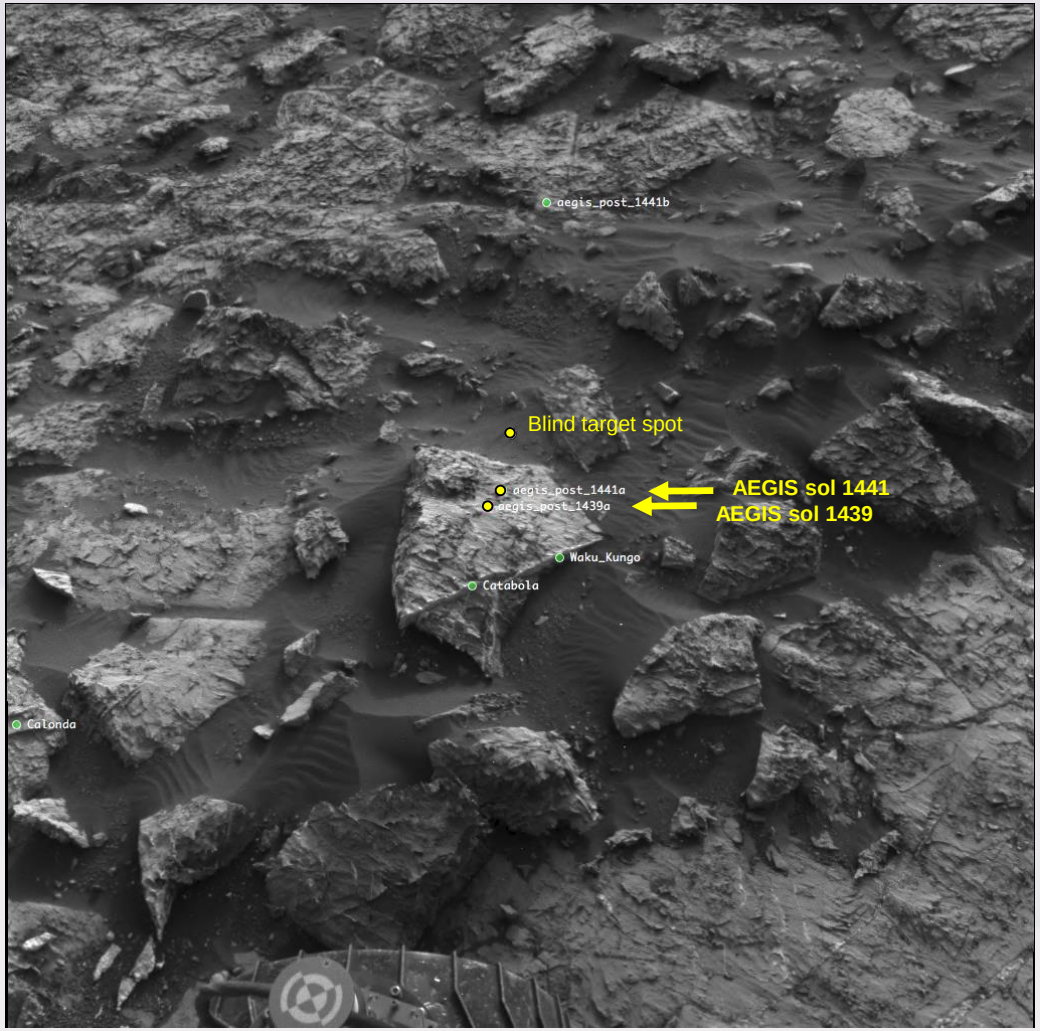


Lighting robustness

Accidental vision experiment

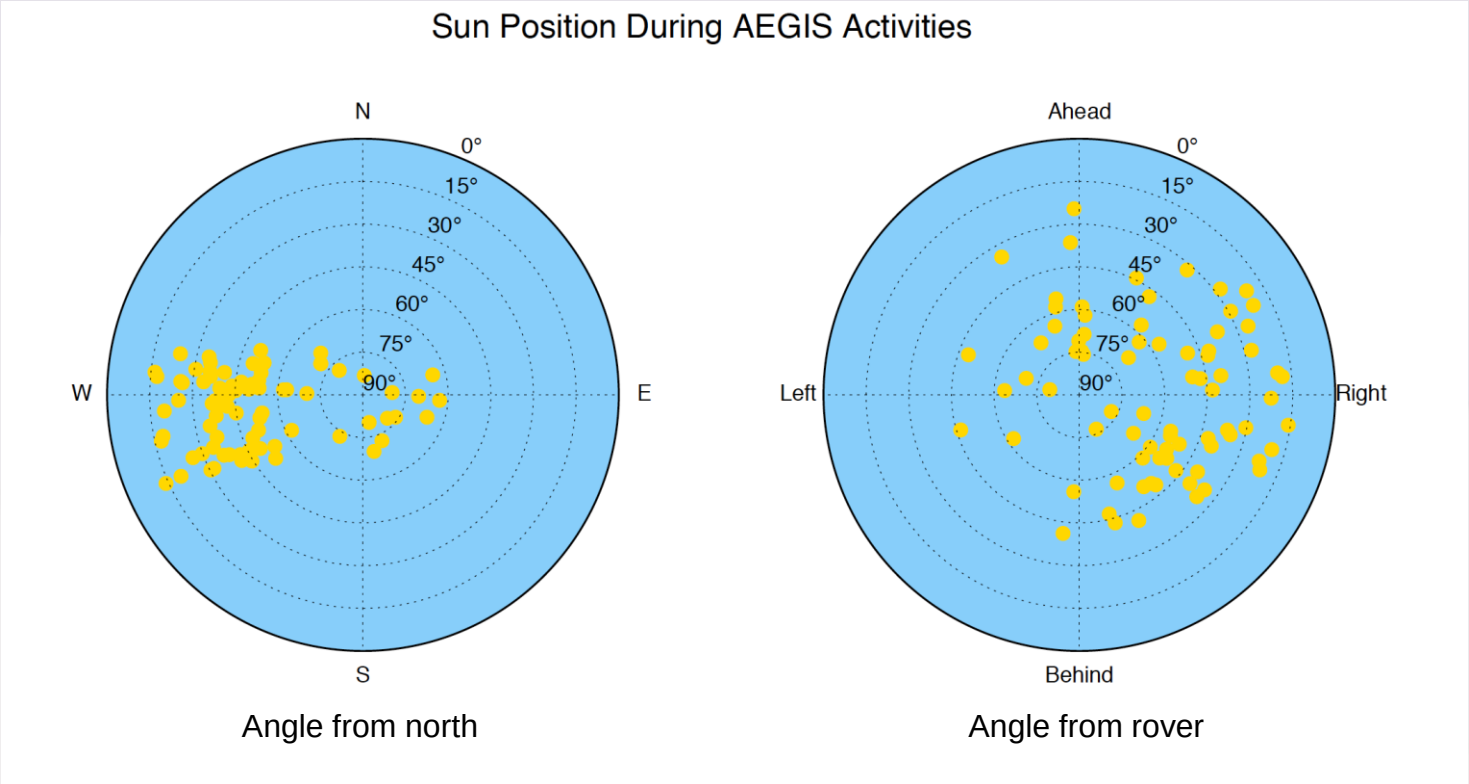
- Sol 1441 drive failed, so post-drive AEGIS FOV was nearly identical to sol 1439
- Sol 1439: 15:40 LTST
- Sol 1441: 16:49 LTST
- Despite shadows and small orientation change, top targets in each run are adjacent (same part of same block)





Lighting robustness

AEGIS autonomous targeting performs well across the range of lighting conditions we've seen



Solar elevation and angle (time of day)

Lighting direction and shadow orientation

Sol 1612: Highest chlorine

Highest concentration of chlorine ever measured by ChemCam on Mars

(So high it strains the calibration)

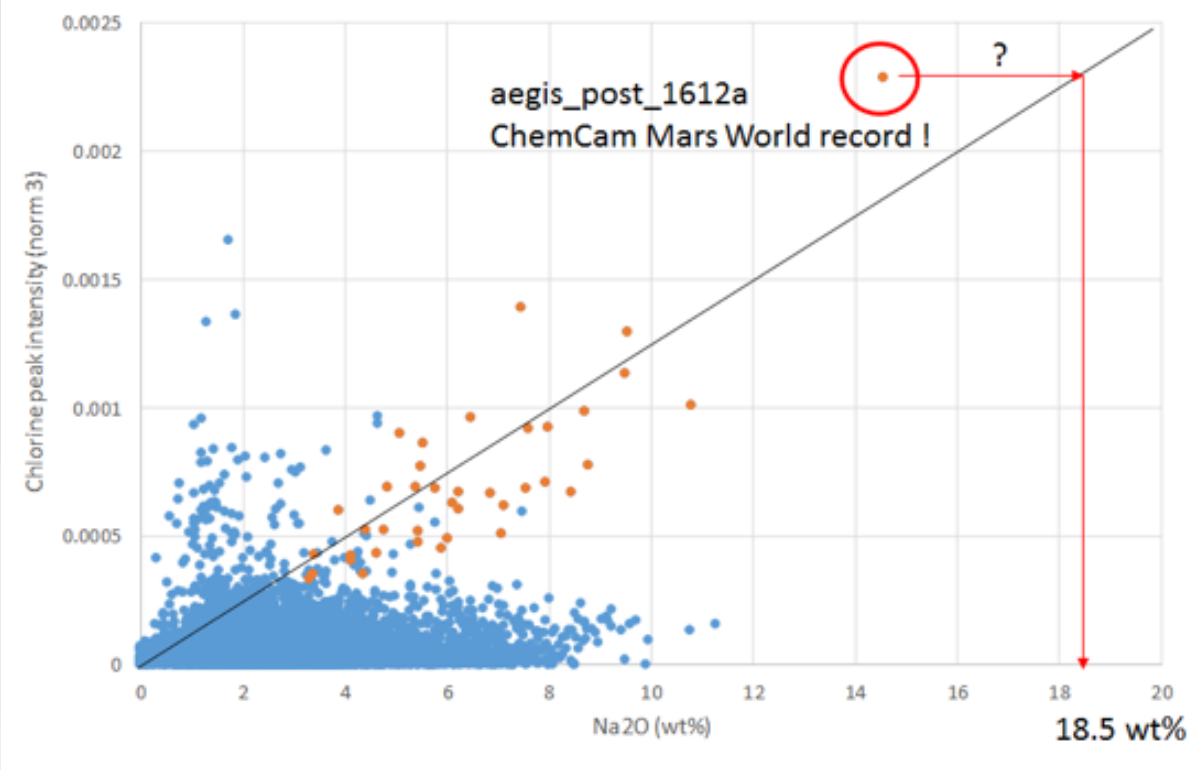


Figure from Pierre-Yves Meslin

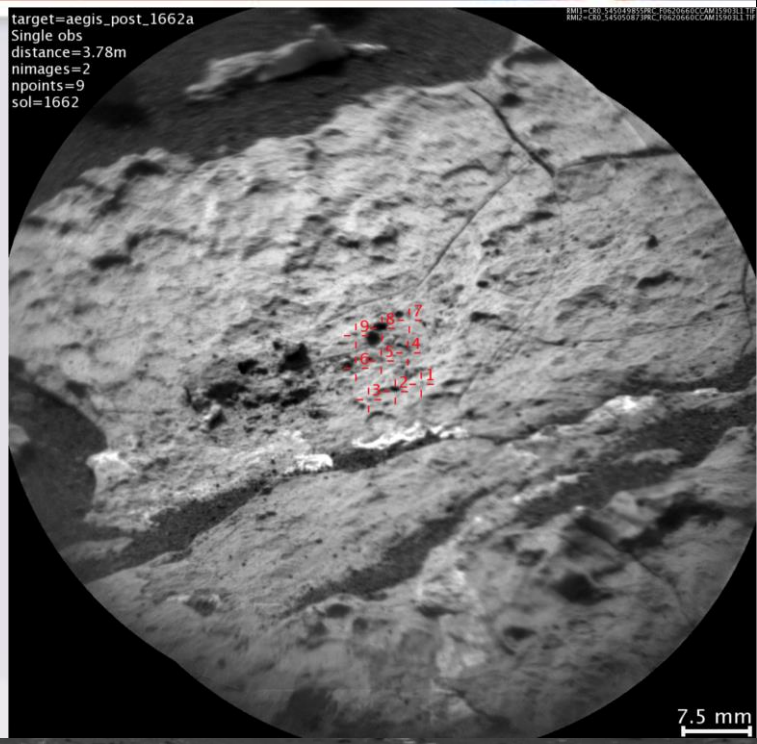
Notable events

Sol 1662: Finding unusual chemistry

Rock was visually unremarkable

Points 5 & 8 had notable chemistry for the local bedrock, with certain elemental abundances unusual

Team spent a targeted observation revisiting this spot.



Notable events

Uplink Reports: Sol 1672 printable page turn help dialogs on help!

ChemCam Eng PUL Report complete (Last updated by suzirgor at 2017-04-19 20:32:28 GMT)

Summary [toggle edit] *posted by suzirgor 2017-04-19 20:30:42 GMT* [history]

Pre-SOWG
Today is a 1-sol plan for sol 1672. There were JPL connectivity issues preventing VPN login until 15 minutes before SOWG. The CCAM team could not see anything in MSLICE so the GEO KOP put in a standard post-drive AEGIS observation for the plan.

Sol 1672:

- 15002 TEC On
- 15700 Power On
- 15903 AEGIS_Navcam_postdrive_3x3_2bpp
- 15003 Power Off
- 15000 Clean Up
- 15910 AEGIS Clean Up

Sol 1672: Networking problems

Problems on the ground kept operators from being able to safely target instruments on Mars.

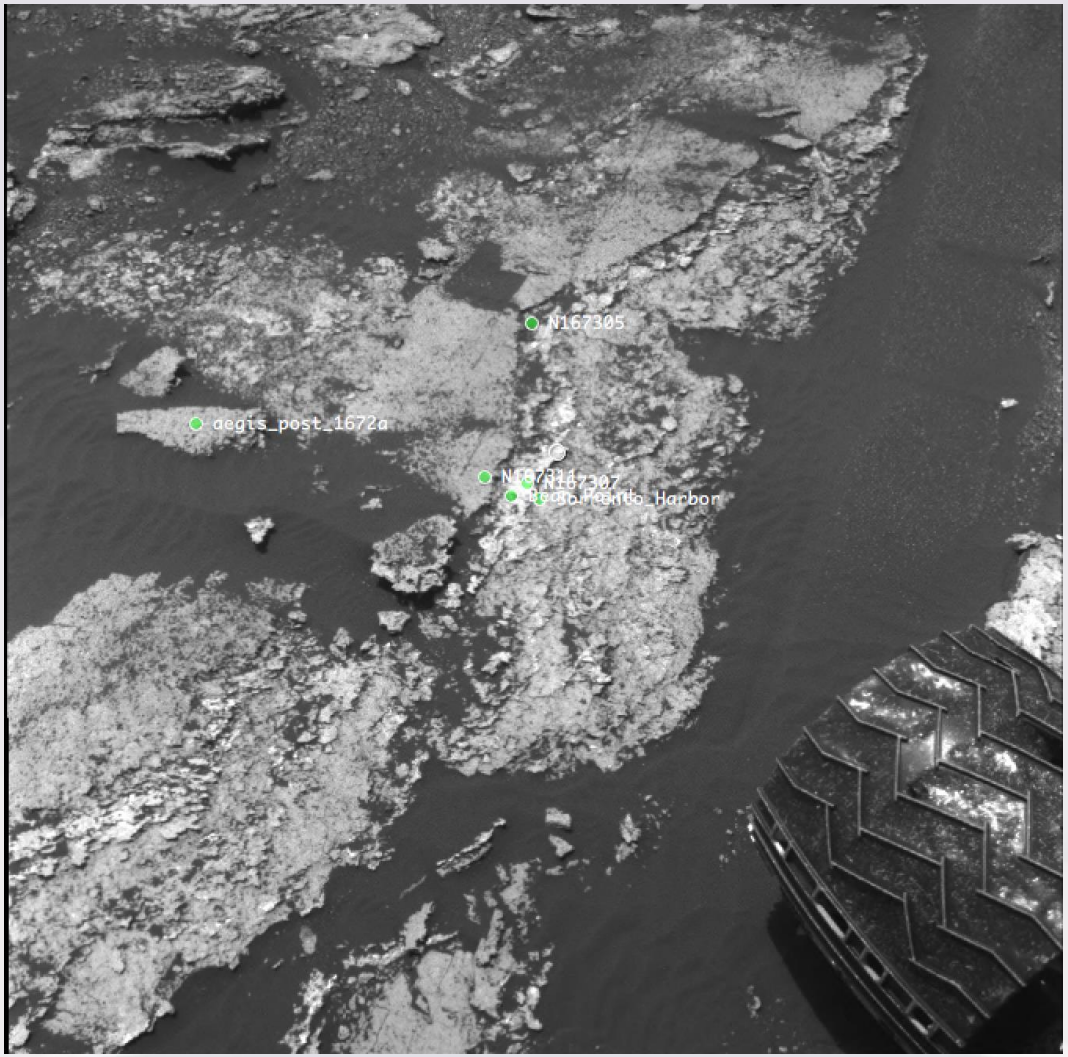
AEGIS-guided ChemCam observations were the only kind possible.

Notable events

Sol 1673: Collect all 3

Upper, smooth material
Brighter vein
Lower, rough material

AEGIS had already measured the upper unit, allowing a complete survey with only 2 targeted measurements

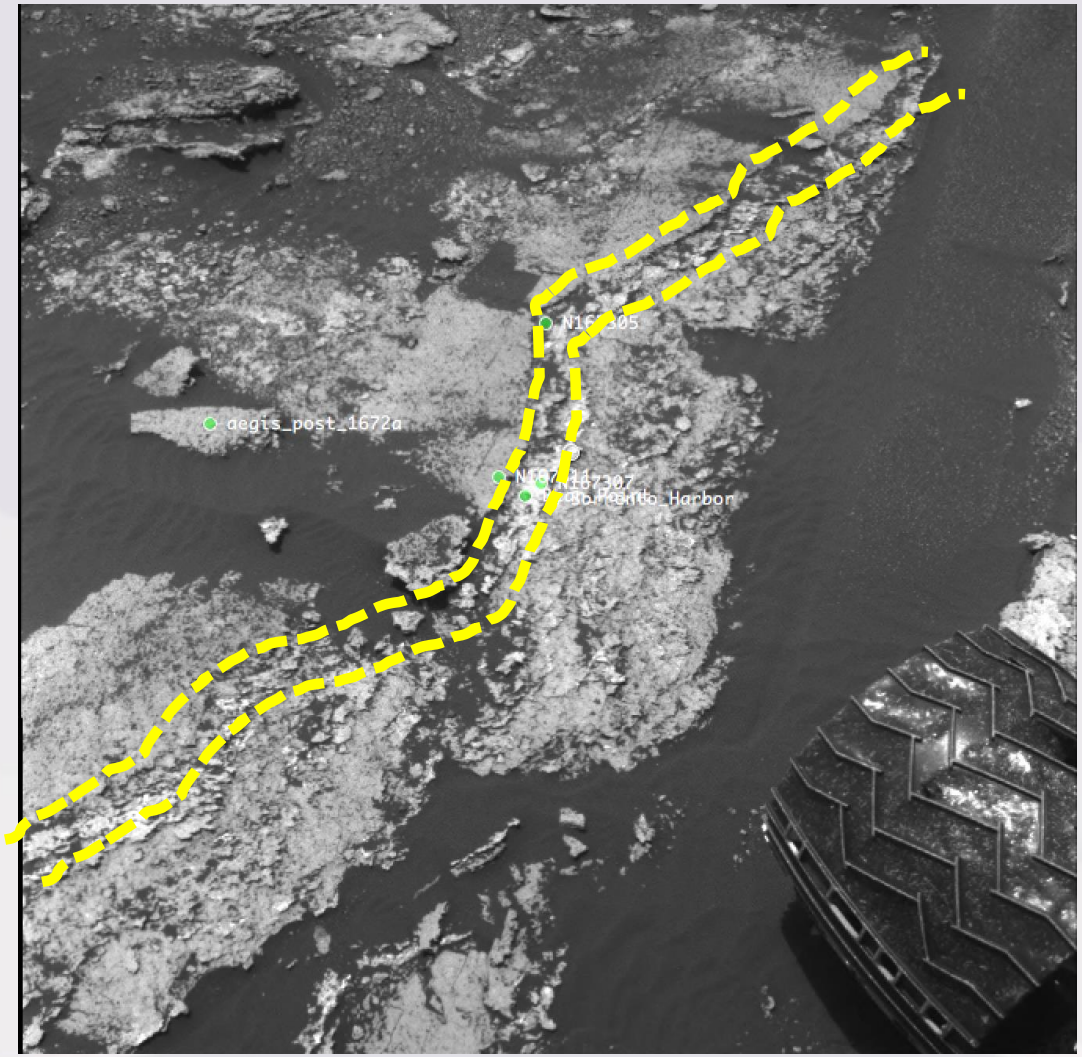


Notable events

Sol 1673: Collect all 3

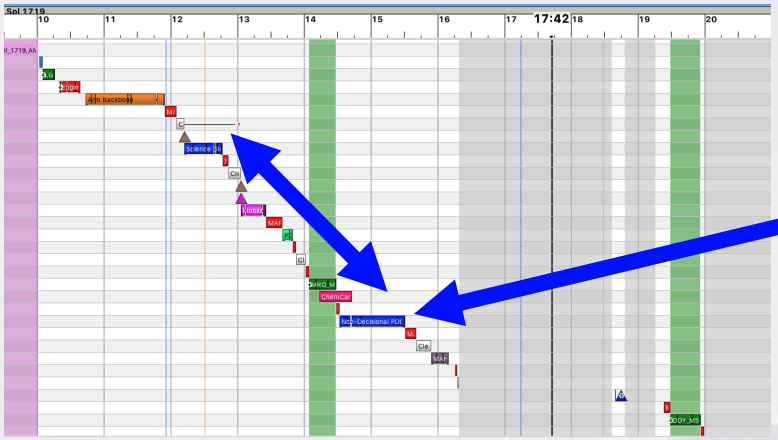
1) Upper, smooth material
2) Brighter vein
3) Lower, rough material

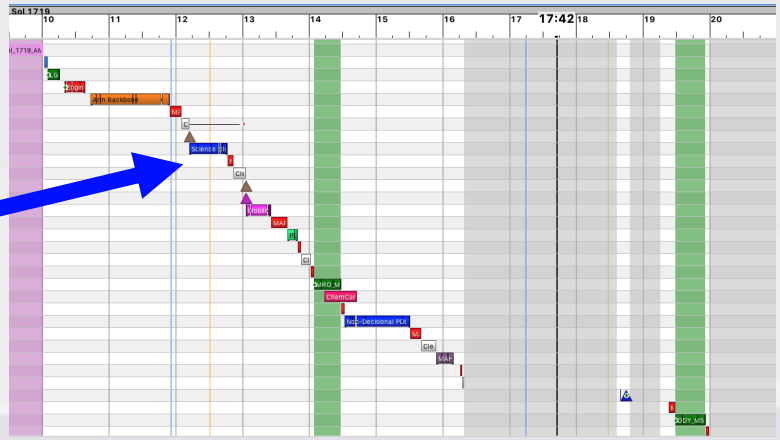
AEGIS had already measured the upper unit, allowing a complete survey with only 2 targeted measurements



New approaches

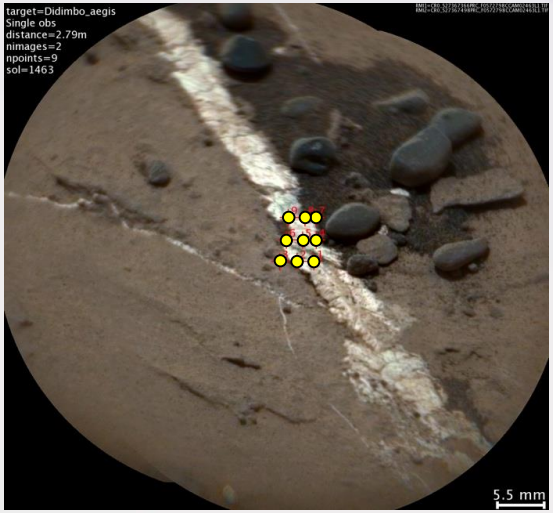
- Background bedrock survey along the rover's traverse
- Free up targeted time for other things
- Mitigate difficulties on the ground
- Making up for limited targetable time (contact science campaigns, engineering work)
- Following up tactically on serendipitous discoveries

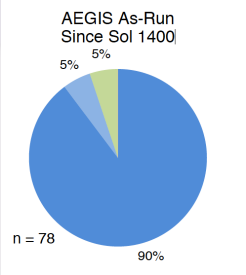


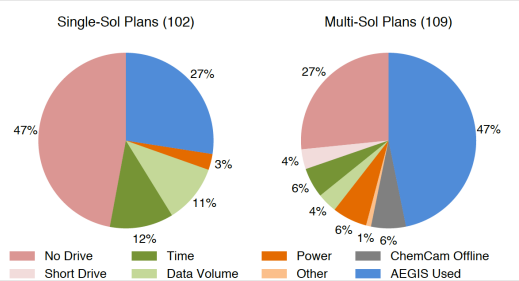


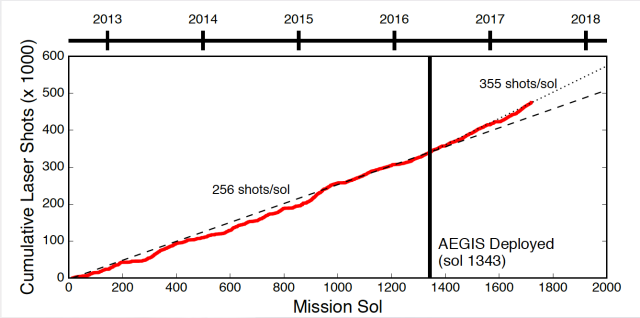
Conclusions

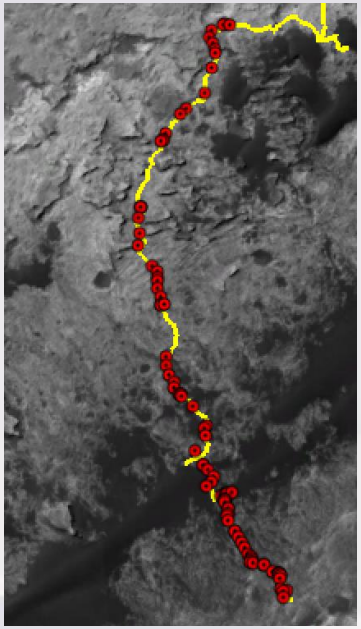
- AEGIS team is very pleased with system performance to date
  - Feedback from science team has been very positive
  - 2 ‘pointing-assured’ targets
  - 88 ‘bonus observations’
  - AEGIS-guided observations often inform next sol’s tactical decisions





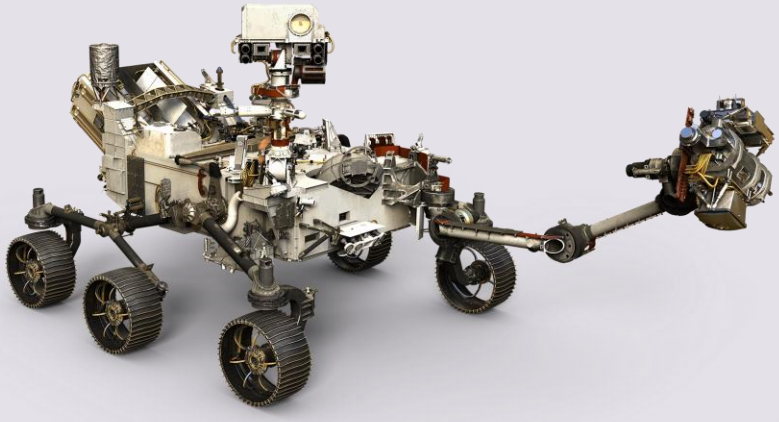


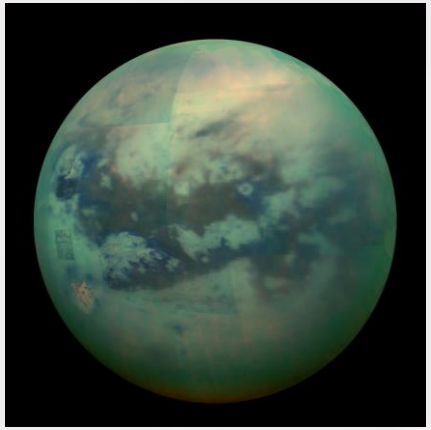




Future

- AEGIS is baselined for Mars 2020
  - SuperCam, the successor to ChemCam
  - Other mast-mounted instruments
- Potentially, throughout the solar system
  - Long light-time delays
  - Lack of relay support
  - Short mission lifetimes
  - Desire to increase science return
  - Speed mission progress





AEGIS deployment & Ops team

AEGIS deployment relied on AEGIS, MSL, and ChemCam teams:

AEGIS

Tara Estlin (AEGIS PI)
Daniel Gaines
Raymond Francis
Gary Doran
Vandi Verma
Benjamin Bornstein
Michael Burl

And of course:

Larger AEGIS development team
ChemCam ops personnel
MSL engineering ops team
MSL science ops team

ChemCam

Roger Wiens (ChemCam PI)
Steven Johnstone
Suzi Montaño
Olivier Gasnault
Laurent Peret
Eric Lorigny
Diana Blaney
Jens Frydenvang
Valérie Mousset

MSL

Deb Chattopadhyay
Betina Pavri