Joshua Vander Hook, Technical Group Supervisor
Artificial Intelligence, Observation Planning & Analysis
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University of Minnesota, April 20, 2022

Sensing and Estimation for Past and (maybe) Future Mars Rovers

Jet Propulsion Laboratory
California Institute of Technology

Where to find these slides?

josh.vanderhook.info

publications/
after 4/21/22

Joshua Vander Hook

Home | Publications | Teaching | Ph.D Thesis | Resume

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Buy me a coffee:[Ko-Fi]

About

Josh is a Computer Scientist, NIAC Fellow, and Technical Group Supervisor at NASA JPL. He has worked on exploration, science, and defense projects while there, including deploying operational autonomous systems for the US Navy. He manages the Artificial Intelligence, Observation Planning and Analysis Group which is responsible for designing and deploying autonomous planning, sequencing, and scheduling to NASA instruments, robots, and spacecraft. The members of the group currently manage or contribute to deep ocean and under-ice robotic explorers, the International Space Station earth observing OCO-3, the Mars Perseverance and Curiosity rovers, Europa Clipper, Psyche Asteroid Mission, NISAR, and several DoD missions.

Previously he was a member of the Maritime and Multi-Agent Autonomy group, where he has had the pleasure of working since 2015.

He completed a Ph.D in the department of Computer Science at the University of Minnesota in Minneapolis in 2015 with Dr. Volkan Isler, and the Robotic Sensor Networks lab. Josh's thesis concerned competitive, online algorithms applied to multi-robot path-planning for sensing, e.g., using robots to mine geo-statistical data for precision agriculture and track invasive species in Minnesota lakes.

Josh enjoys boxing, climbing, camping, sailing, live music, and road-biking. He also occasionally does pro bono curriculm development for non-profit educational and STEM outreach organizations, including Mind Makers.

News

2021 Mar: Excited to present to WVU!

- AI for Spacecraft at NASA JPL. Virtual talk, 2021.
  [slides]

2021 Jan: Presented to AAS 2021

- Nebulae: KISS In-Situ Cloud Computing Workshop for Space Exploration Missions
  American Astronomical Society 2021, Virtual.
  [slides]

2021 Jan: A few publications related to Decadal Survey and the MOSAIC Planetary Mission Concept

NASA funded study on a constellation of orbiters for studying soil, atmosphere, ionosphere interactions at Mars. A huge effort across mutiple institutions, in which I played a small part.

And, an LPSC conference presentation by Rob Lillis, the PI, on the topic.

- **MOSAIC: Mars Orbiters for Surface Atmospheric and Ionospheric Connections**
  Robert Lillis, David Mitchell, Steve Matousek, et al.
  NASA Planetary Science Decadal Survey, National Academies of Science August 2020.
  [pdf] [bib] [National Academies Slides]
- **MOSAIC: Mars Orbiters for Surface Atmospheric and Ionospheric Connections**
  R. J. Lillis, N. G. Heavens, L. Montabone, S. Guzewich, S. M. Curry, P. Withers, M. Chaffin, T. N. Harrison, C. O. Ao, D. L. Mitchell, J.G. Luhmann, J. I. Deighan, M. Kahre, A. Brecht, C. Neish, , J. Vander Hook, I. Smith, , S. L. England, B. M. Jakosky, S. Matousek, C. Edwards
  AGU Fall Meeting 2020.
  [pdf] [bib]

2021 Jan: New paper for IEEE Aerospace Conference

What does our group/section do?
(shamelessly borrowed)

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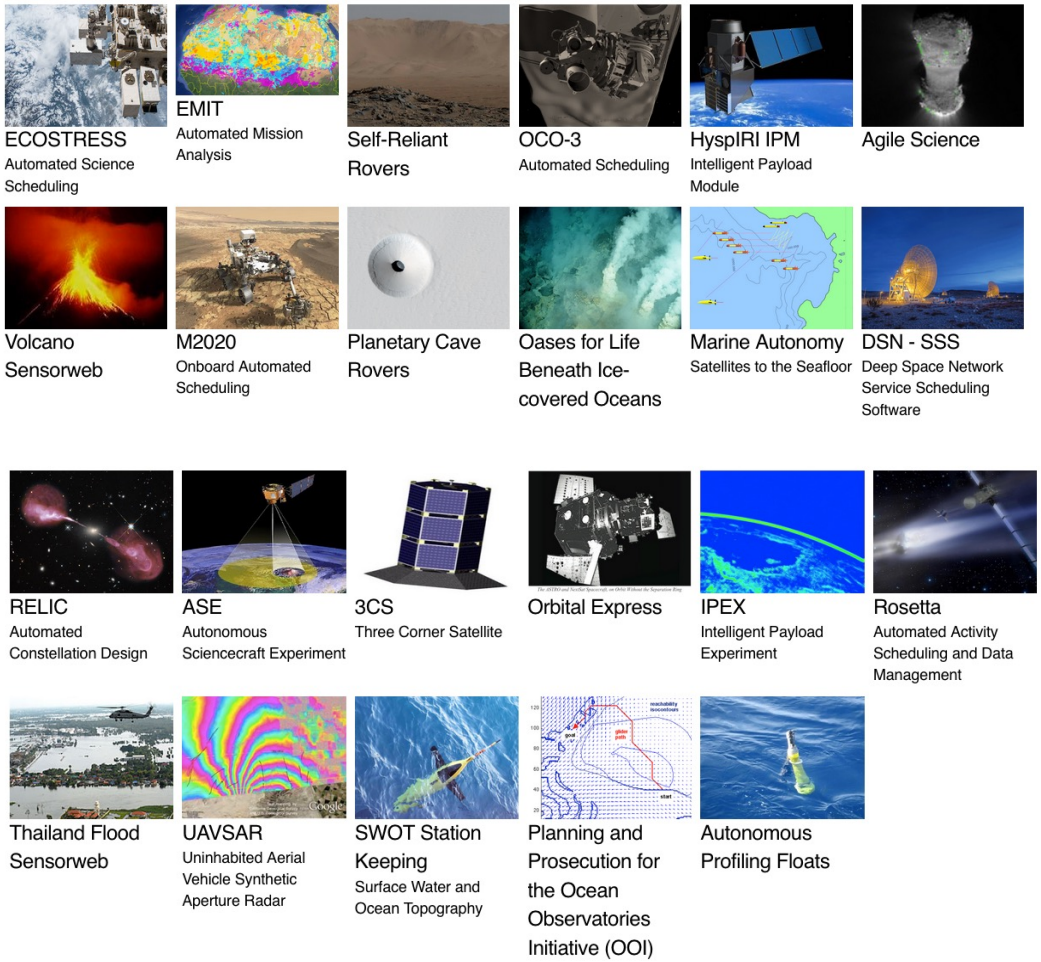
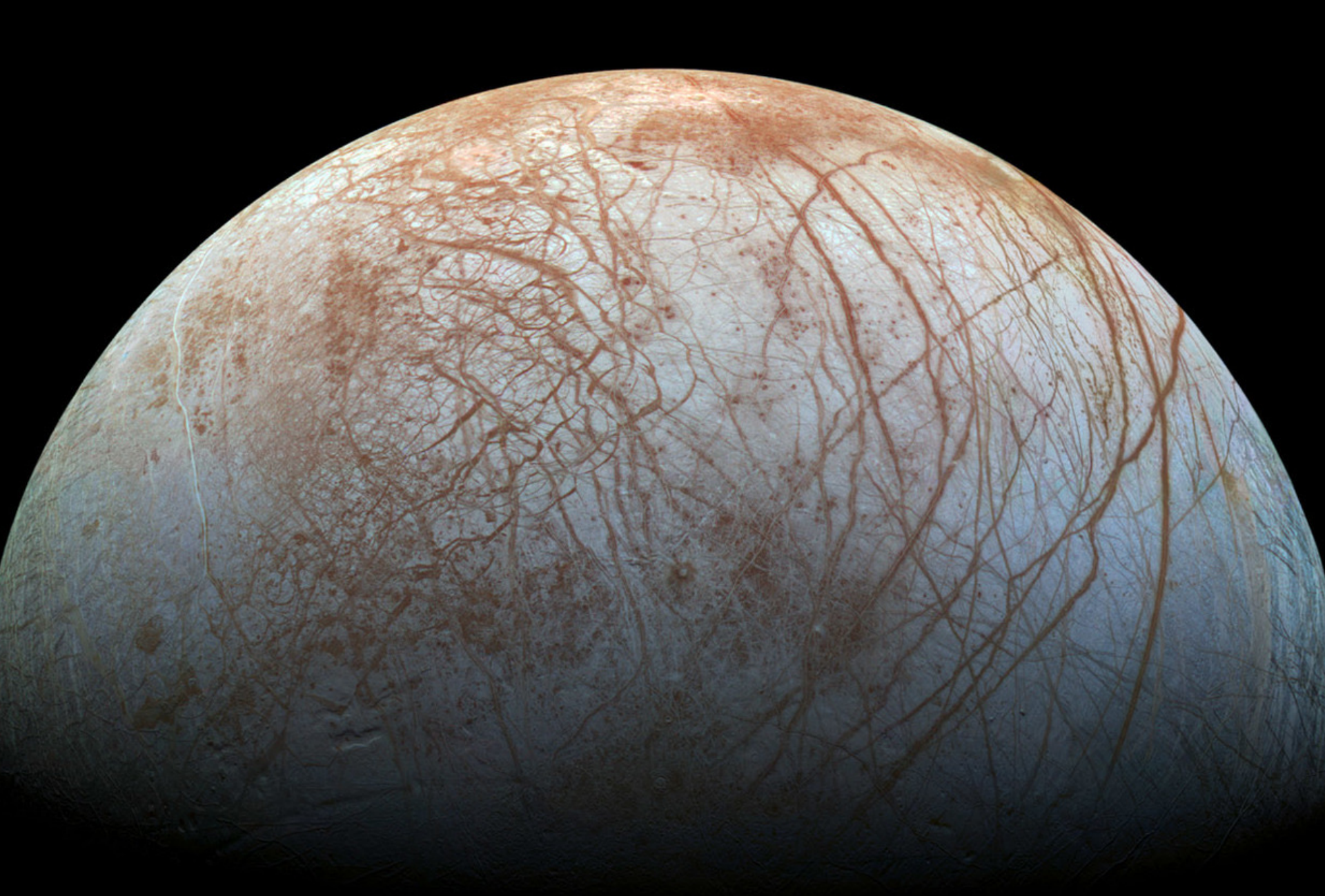
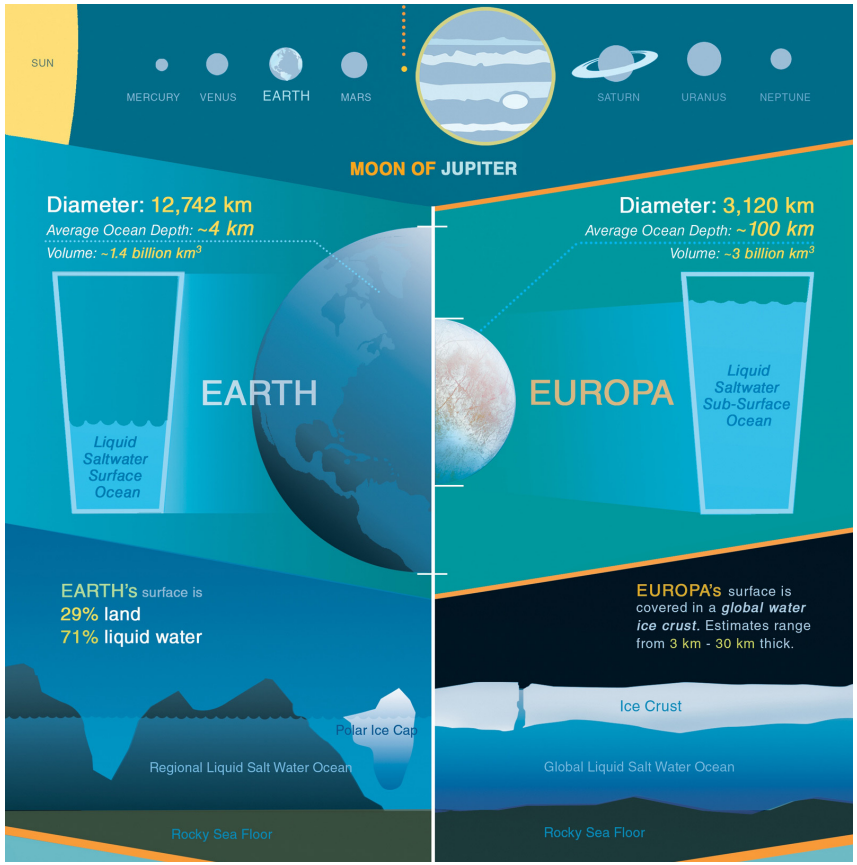
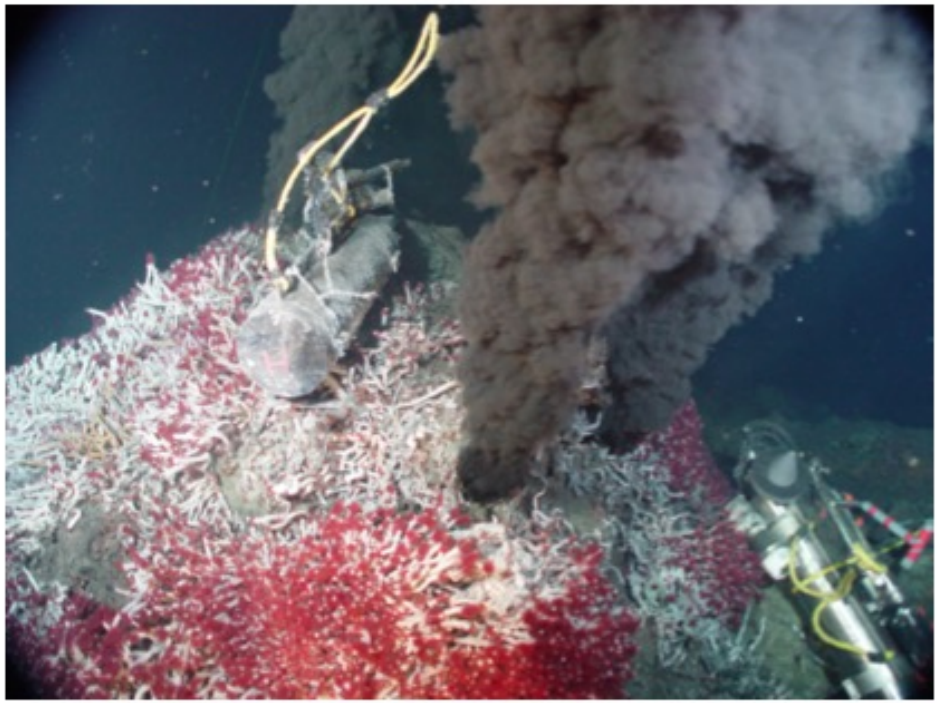
ml.jpl.nasa.gov
dus.jpl.nasa.gov





Go watch this brief overview by astrobiologist Kevin Hand
https://www.jpl.nasa.gov/videos/europa-ocean-world



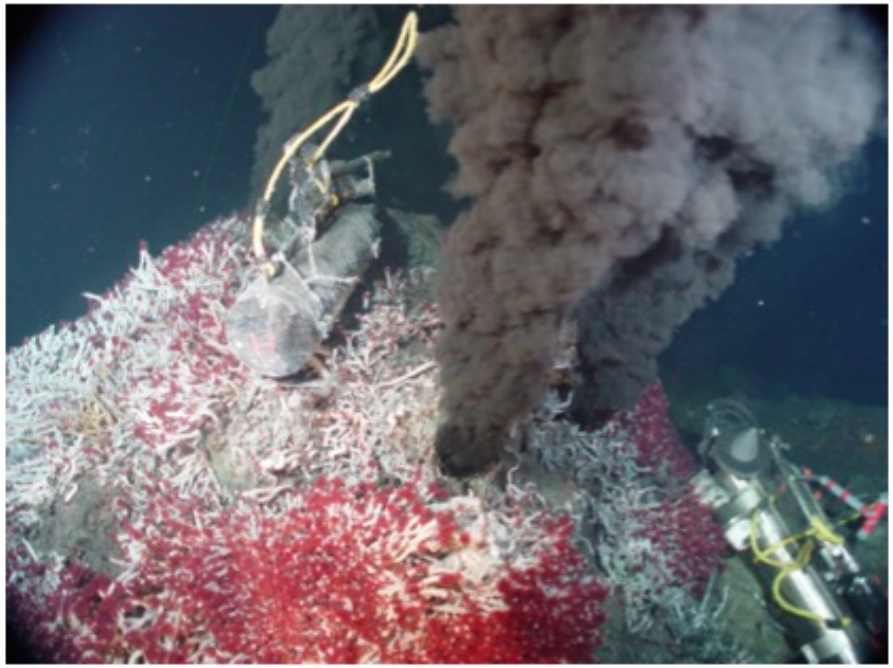


Credit: IFE, URI-IAO, UW, Lost City Science Party; NOAA/OAR/OER; The Lost City 2005 Expedition

Autonomous Science

Hydrothermal Venting

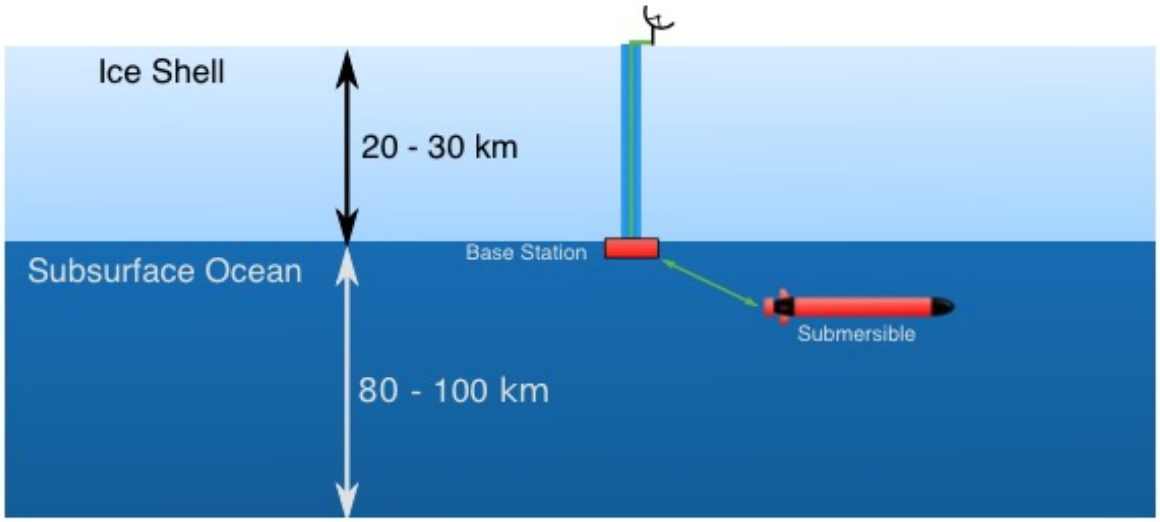
- Detecting and tracking of scientific features of interest
- Requires encoding of expert knowledge of scientific phenomena into autonomous algorithms
- Hydrothermal Venting is one such phenomena of interest
  - Harbors unique ecosystem based on chemosynthesis
  - Potential for hydrothermal venting on Europa. Evidence for venting on Enceladus
  - Sensors: Temperature, Oxidation Reduction Potential, Optical Backscatter



Credit: IFE, URI-IAO, UW, Lost City Science Party; NOAA/OAR/OER; The Lost City 2005 Expedition

Ocean Worlds Submersible Concept Mission

- Long duration mission
  - 1+ years to penetrate ice plus 1 year mission underwater
  - Travel 100's of km from base station
- 3 main components: Surface antenna, under-ice base station, submersible
- Limited communication windows due to orbital occlusions (~42.5 and ~33 hours per orbital period of Europa and Enceladus respectively). No communication when distant from base station, sometimes 100s of km
- Dynamic environment prevents traditional human in the loop operations (e.g. Mars Rovers)
- Due to environmental and communication constraints, full autonomy is needed for weeks or months at a time.



High-Level Notional Ocean Worlds Submersible Concept

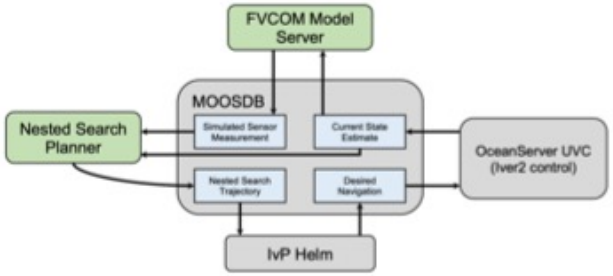
Predecisional, for planning and discussion only

Onboard Autonomy Requirements for an Ocean Worlds Submersible Mission

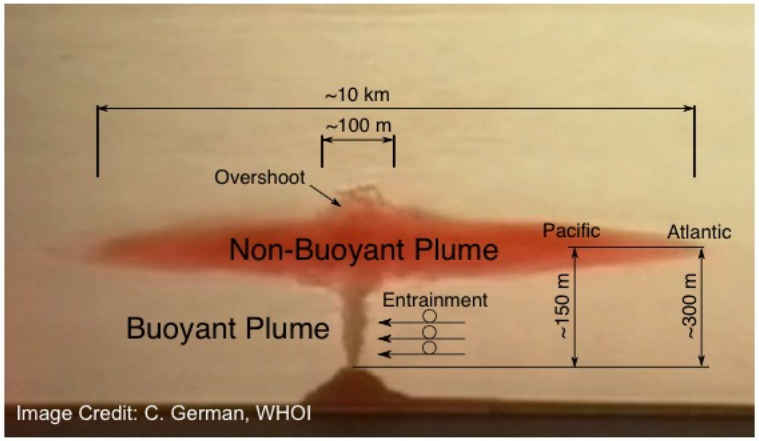
Andrew Branch[1], Steve Chien[1], Brett Hobson[2], Ben Y. Raanan[2], James McMahon[3], Christopher R. German[4], Guangyu Xu[5], Michael V. Jakuba[4]

[1]*Jet Propulsion Laboratory, California Institute of Technology*
[2]*Monterey Bay Aquarium Research Institute*
[3]*Naval Research Laboratory*
[4]*Woods Hole Oceanographic Institution*
[5]*Applied Physics Laboratory, University of Washington*

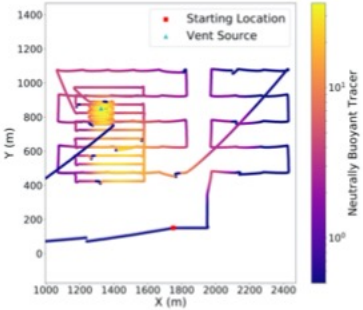
Iver2 AUV parked on the shore at NRL's Chesapeake Beach Detachment after performing an experiment



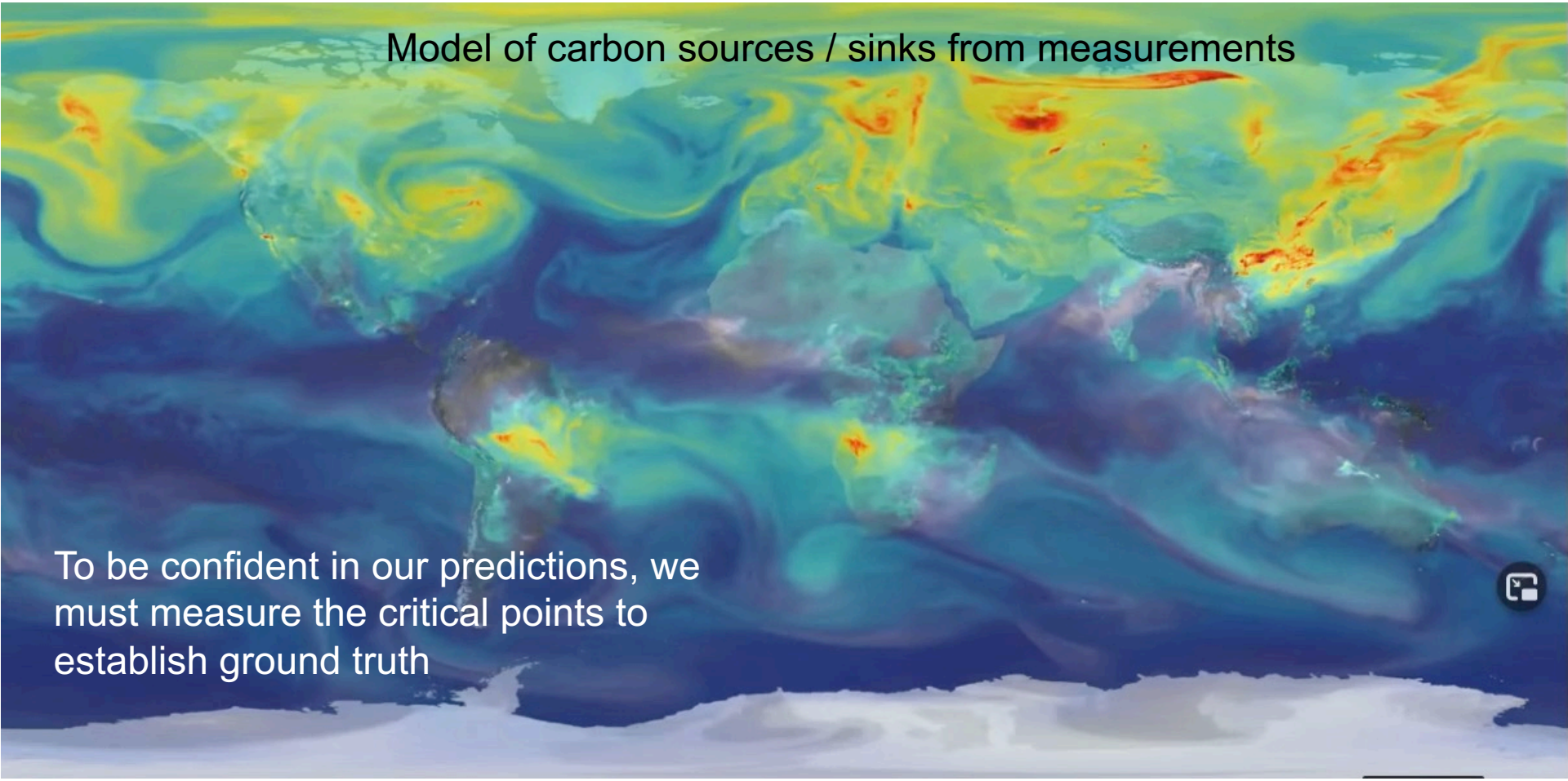
Autonomy architecture, showing the main components required for automated nested search using the Iver2 AUV



- Performed 5 runs over 4 days, successfully located simulated hydrothermal venting.
- Full Simulation Success Rate
  - Nested Search: 80%
  - Greedy Transect: 56%
  - Gradient Ascent: 4%
  - Higher success rates correlate with longer search times



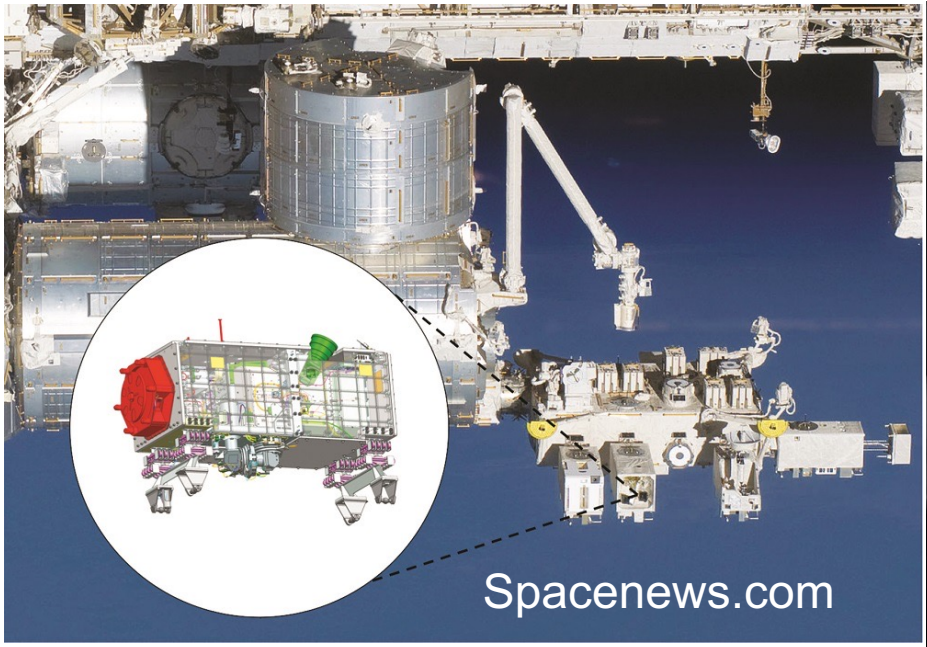
Deployment Results with Simulated Data
The sensed concentration of the neutrally buoyant tracer, starting location, and vent source are plotted.

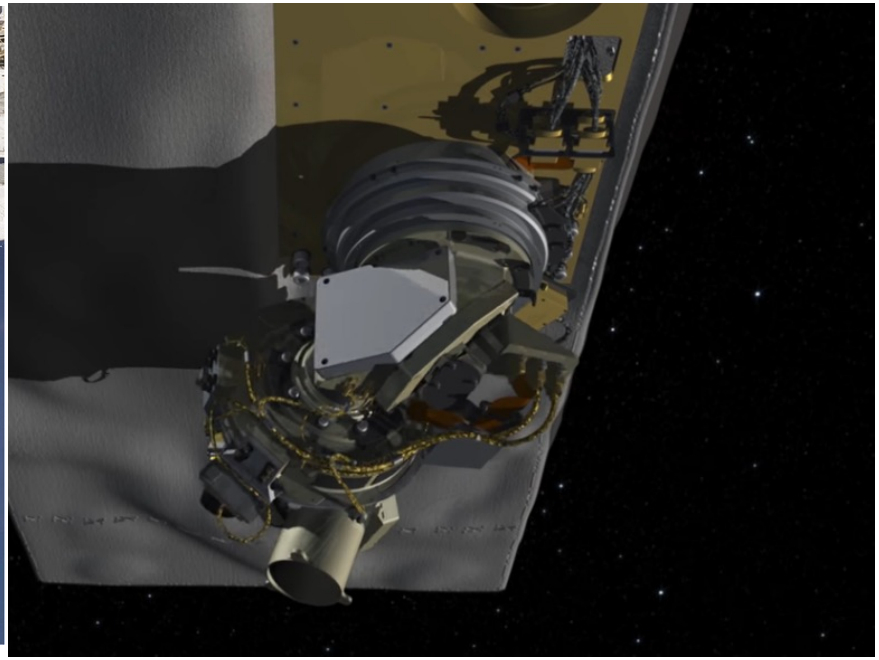


https://www.youtube.com/watch?v=x1SgmFa0r04

Science planning for Orbiting Carbon Observatory-3

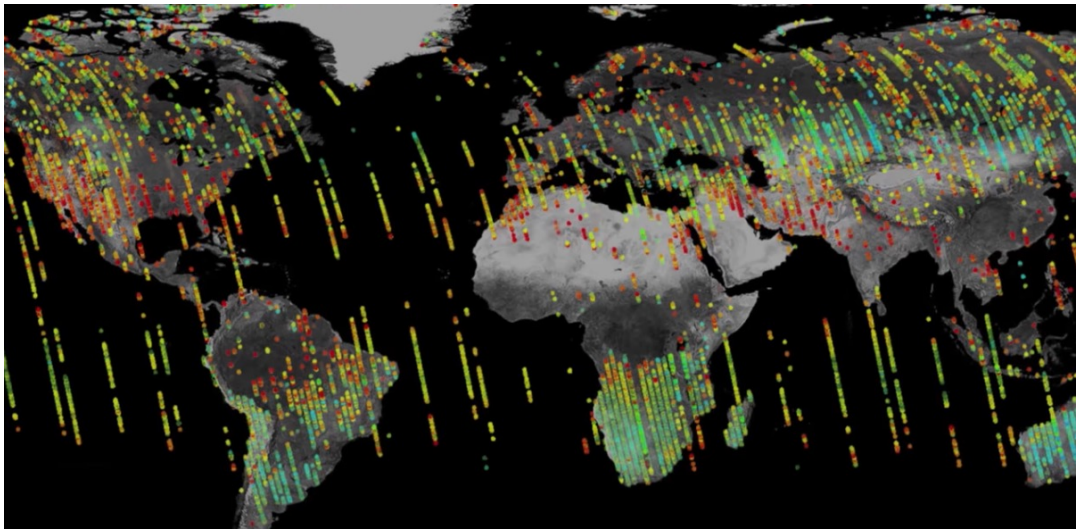
Sensitive spectrometers can measure the rate of environmental absorption of CO2





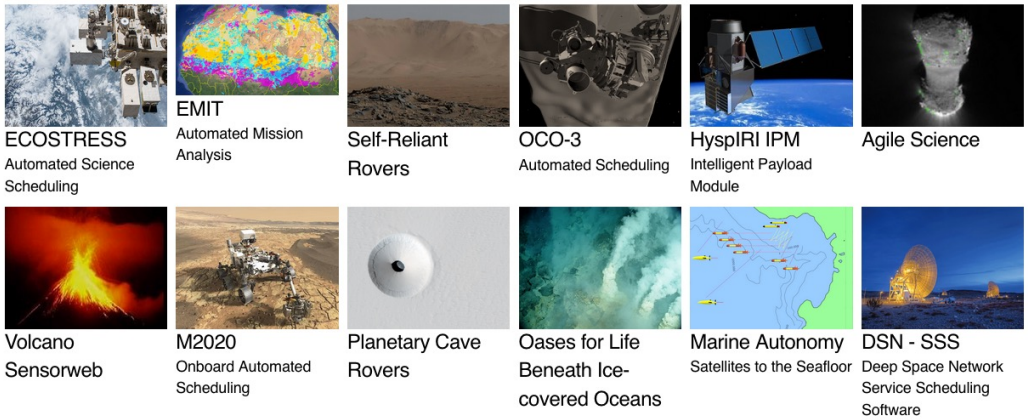
https://www.youtube.com/watch?v=7GMjU5pSufk

Automated instrument pointing from science plans



Challenging constraint satisfaction problem

ai.jpl.nasa.gov
ml.jpl.nasa.gov
dus.jpl.nasa.gov



You'll love this one…

A volcanologist called a colleague at JPL, asking if they could get photos of a volcano that just started erupting, and the spacecraft had already recognized that need and sent the images back the night before (EO-1)

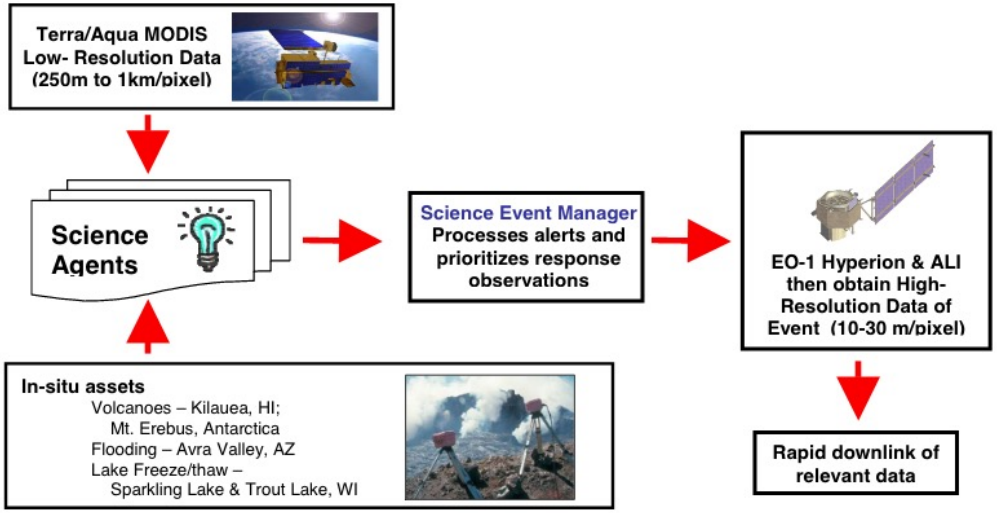
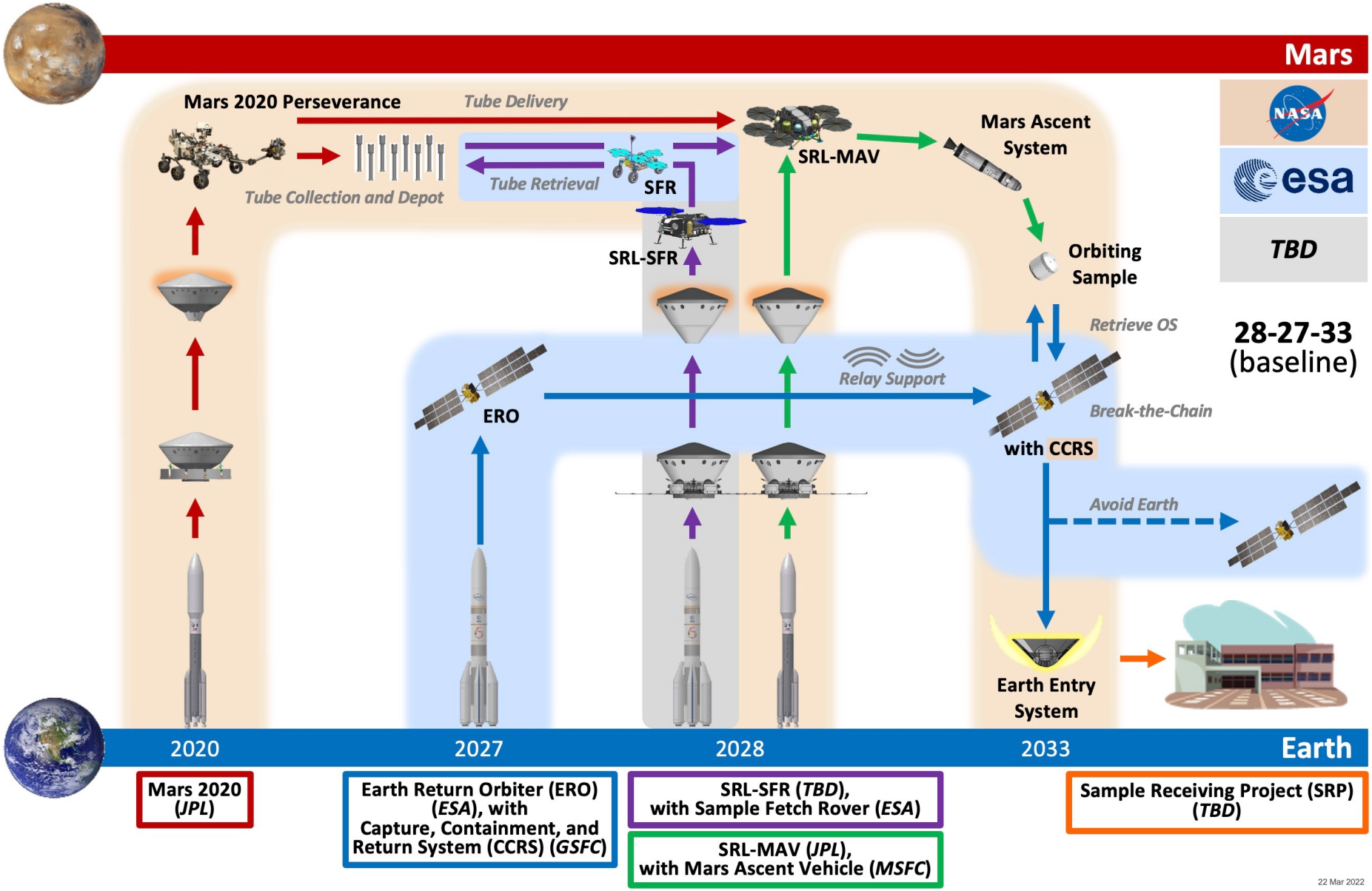


Figure 4. Sensorweb Detection and Response Architecture

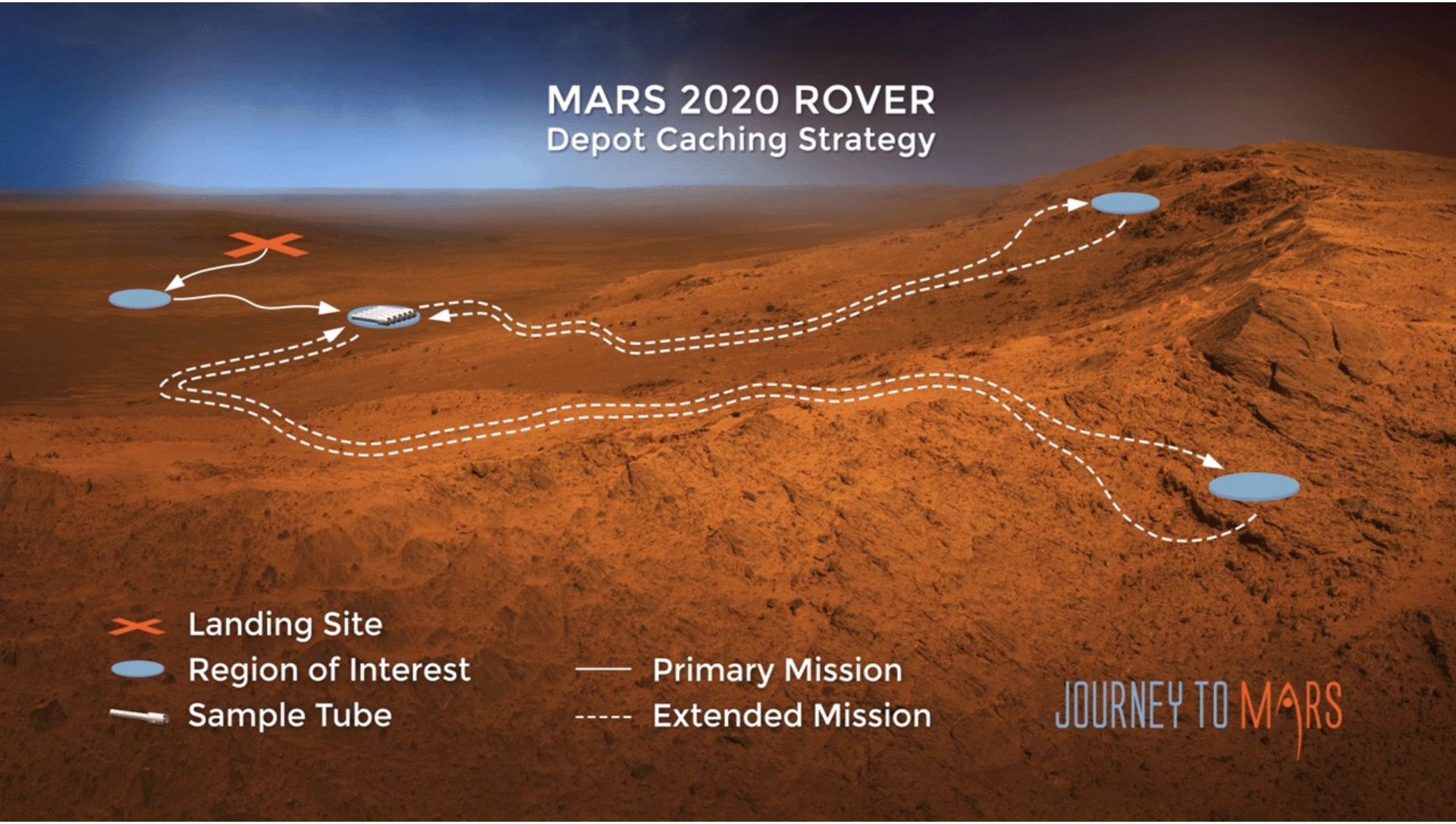
Mars Rovers

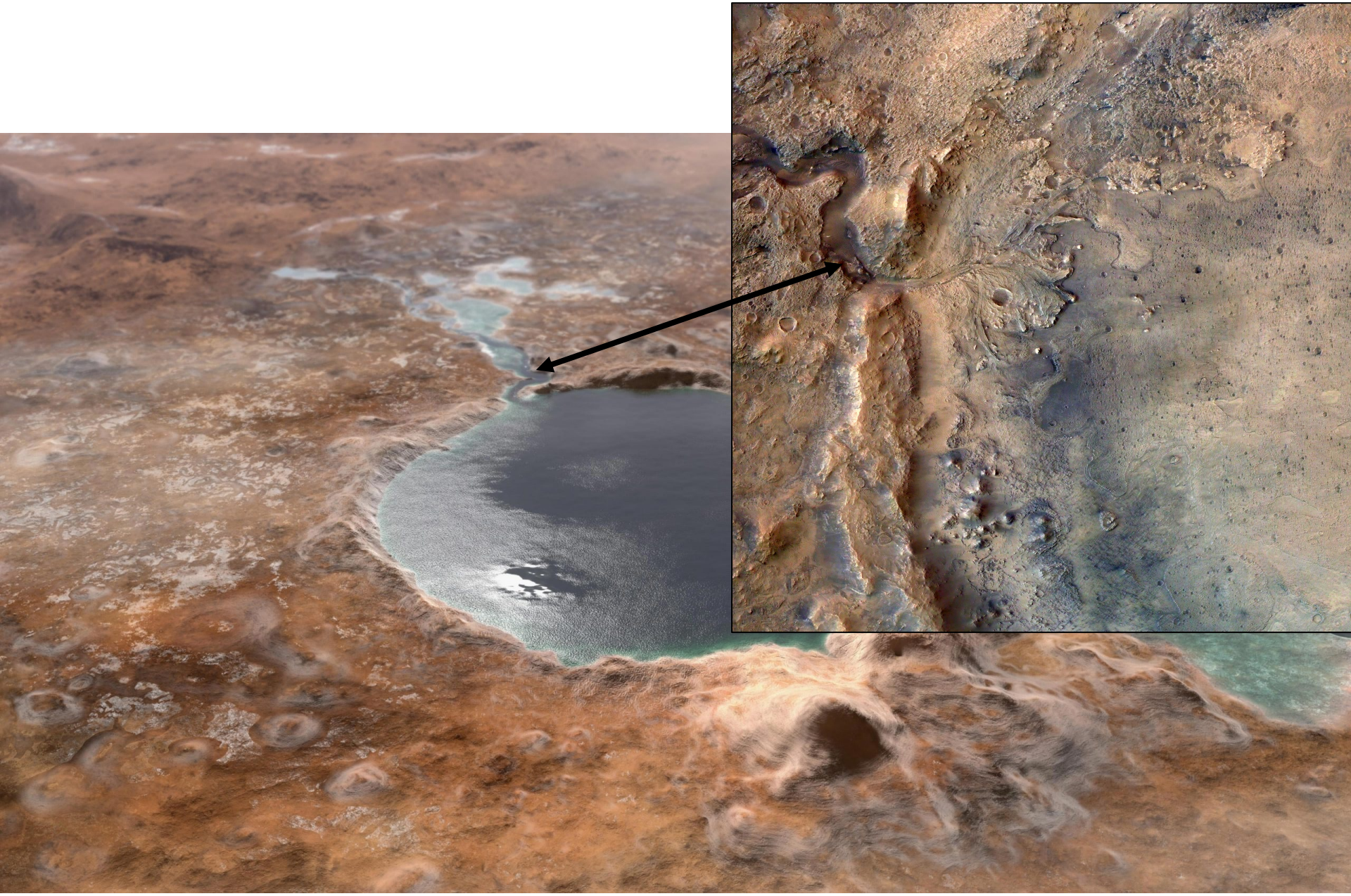
ai.jpl.nasa.gov



Pre-Decisional Information – For Planning and Discussion Purposes Only

Credit: https://mars.nasa.gov/imgs/mars2020/Mars2020-Depot-Caching-animated.gif

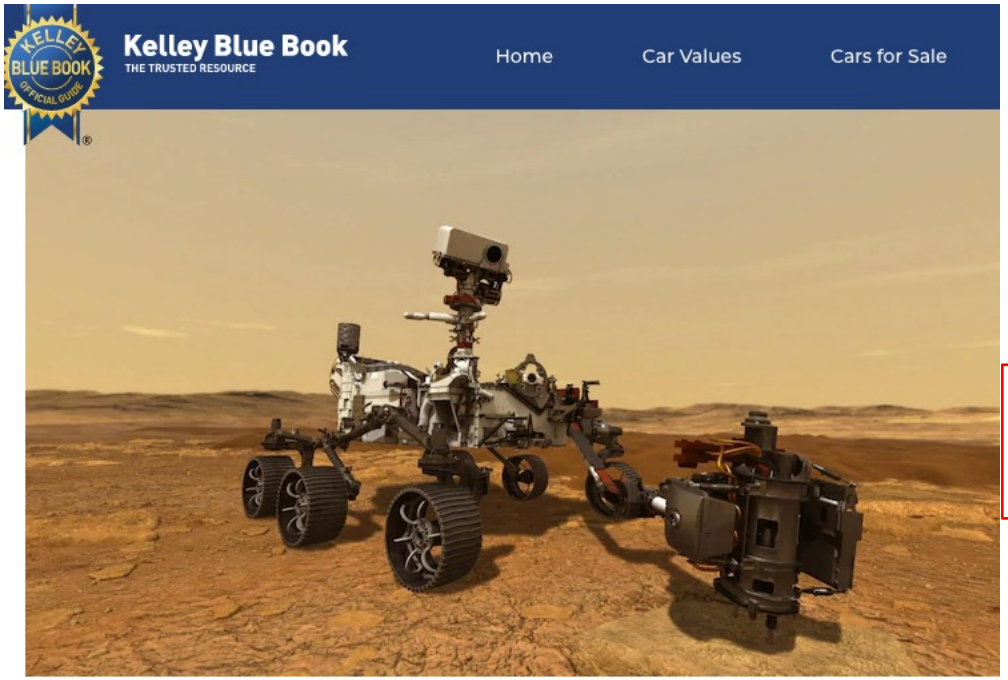




Check out the landing video:

https://www.youtube.com/watch?v=4czjS9h4Fpg

Self-driving rover (sort of)



The 2022 NASA Mars Rover was released (from its atmospheric descent cowl) yesterday. It's a limited edition of one.

Electric Drivetrain

Six electric motors, one per wheel, drive Perseverance. Power comes from a 99-pound radioisotope thermoelectric power generator using 11 pounds of plutonium-238 oxide, making refueling deadly and hopeless.

The suspension is a complex unit NASA calls a "rocker-bogie" design. It works to maintain a relatively constant weight on each of the six wheels as it moves over uneven terrain. Four-wheel steering is standard, as the front and rear wheels can each rotate 360 degrees.

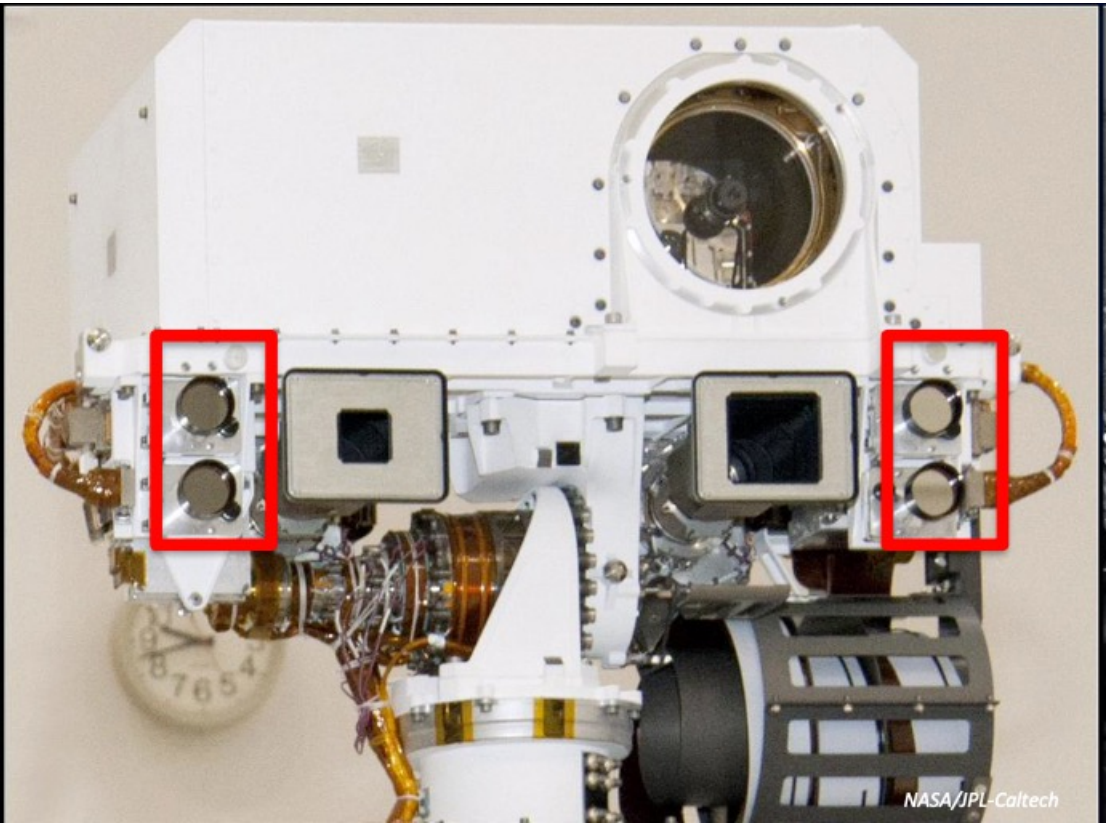
Available only in 6-wheel drive, the rover boasts a top speed of 0.09 mph, good for a new world speed record (think about it). It boasts a 0-to-60 time of nope.

Handling is a bit sluggish, as drivers must send commands from Earth and wait approximately 20 minutes for them to reach the rover on Mars before they can be carried out. However, new self-driving software should allow the rover to make more independent decisions about how to cross obstacles in its path, reducing the need for direct inputs from an earthbound driver.

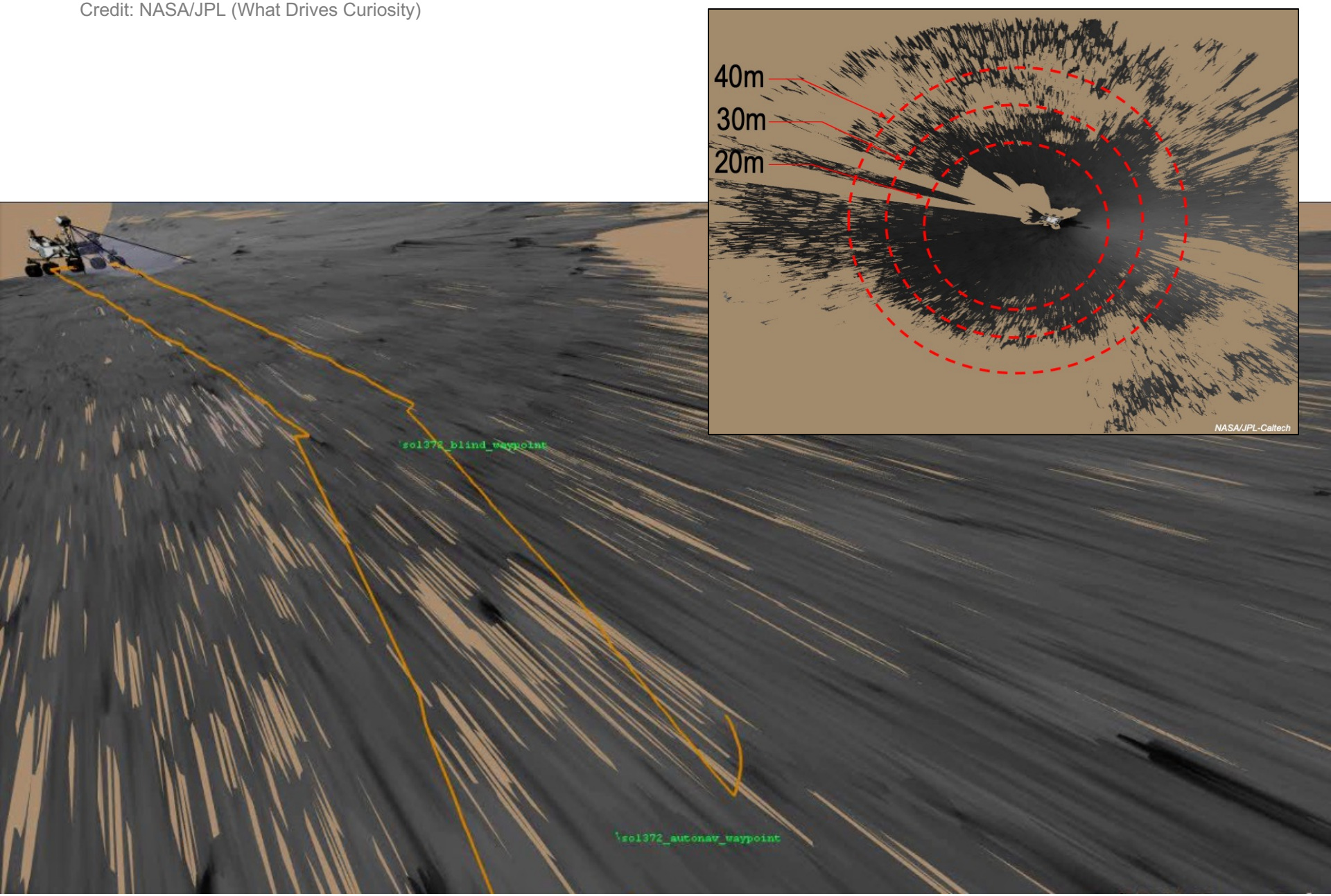
Lightweight aluminum wheels are standard and strengthened for off-road performance on a planet with no roads. "Engineers redesigned the Mars 2020 Perseverance rover's wheels to be more robust due to the wear and tear the Curiosity rover wheels endured while driving over sharp, pointy rocks," NASA explains. "Perseverance's wheels are narrower than Curiosity's, but bigger in diameter and made of thicker aluminum."

Credit: https://www.youtube.com/watch?v=E3xWCqPBUFU

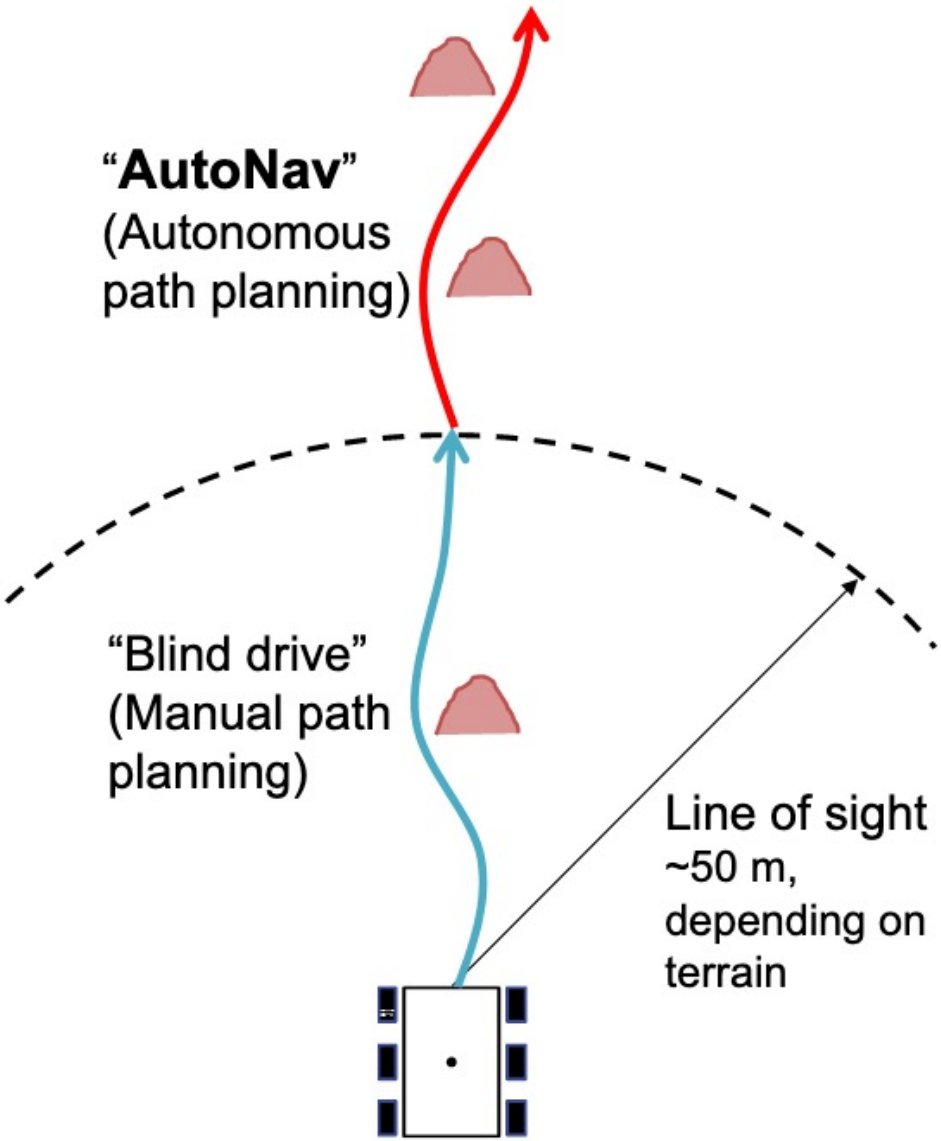
Credit: NASA/JPL (What Drives Curiosity)



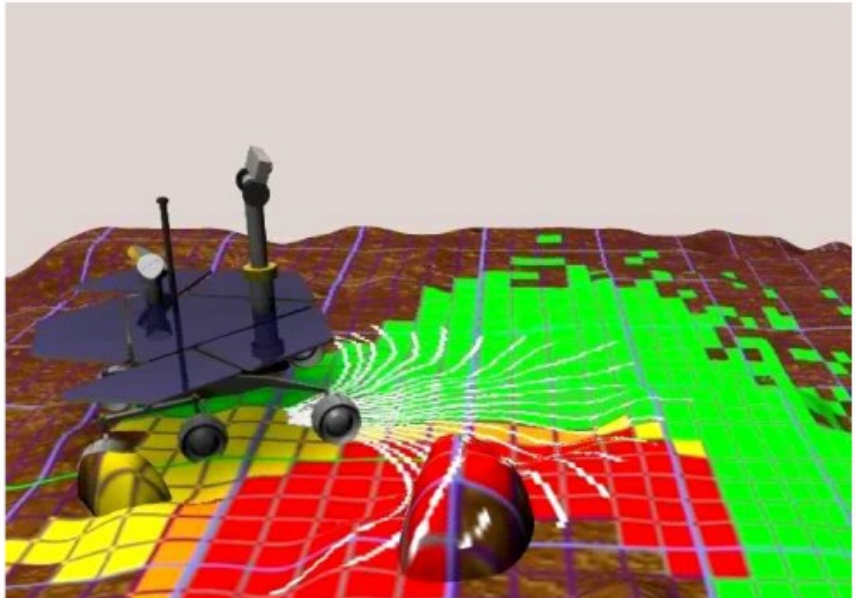
Credit: NASA/JPL (What Drives Curiosity)



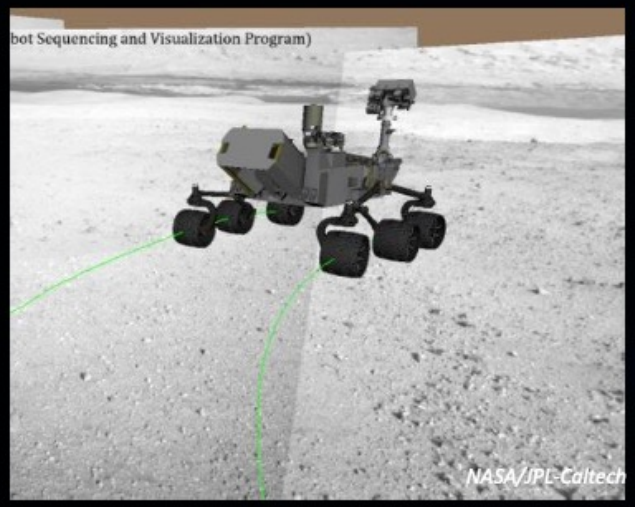
Credit: https://trs.jpl.nasa.gov/bitstream/handle/2014/48231/CL%2317-3124.pdf

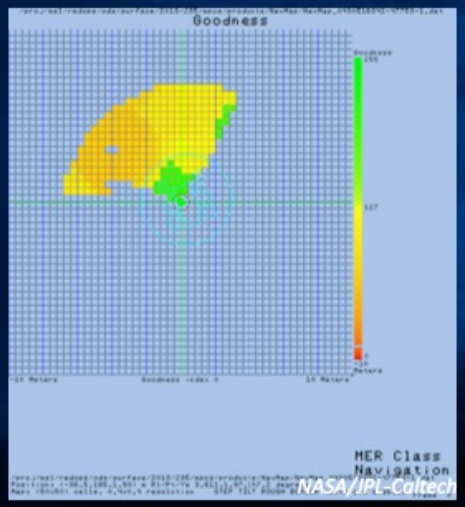


- Manual path planning is limited within the line of sight
- Up/down link: once per Sol (Martian day = 24hr40min)
- AutoNav extends drive distance per Sol beyond the line of sight
- AutoNav successfully drove on MER/MSL rovers



Credit: NASA/JPL “What drives curiosity”





Directed driving

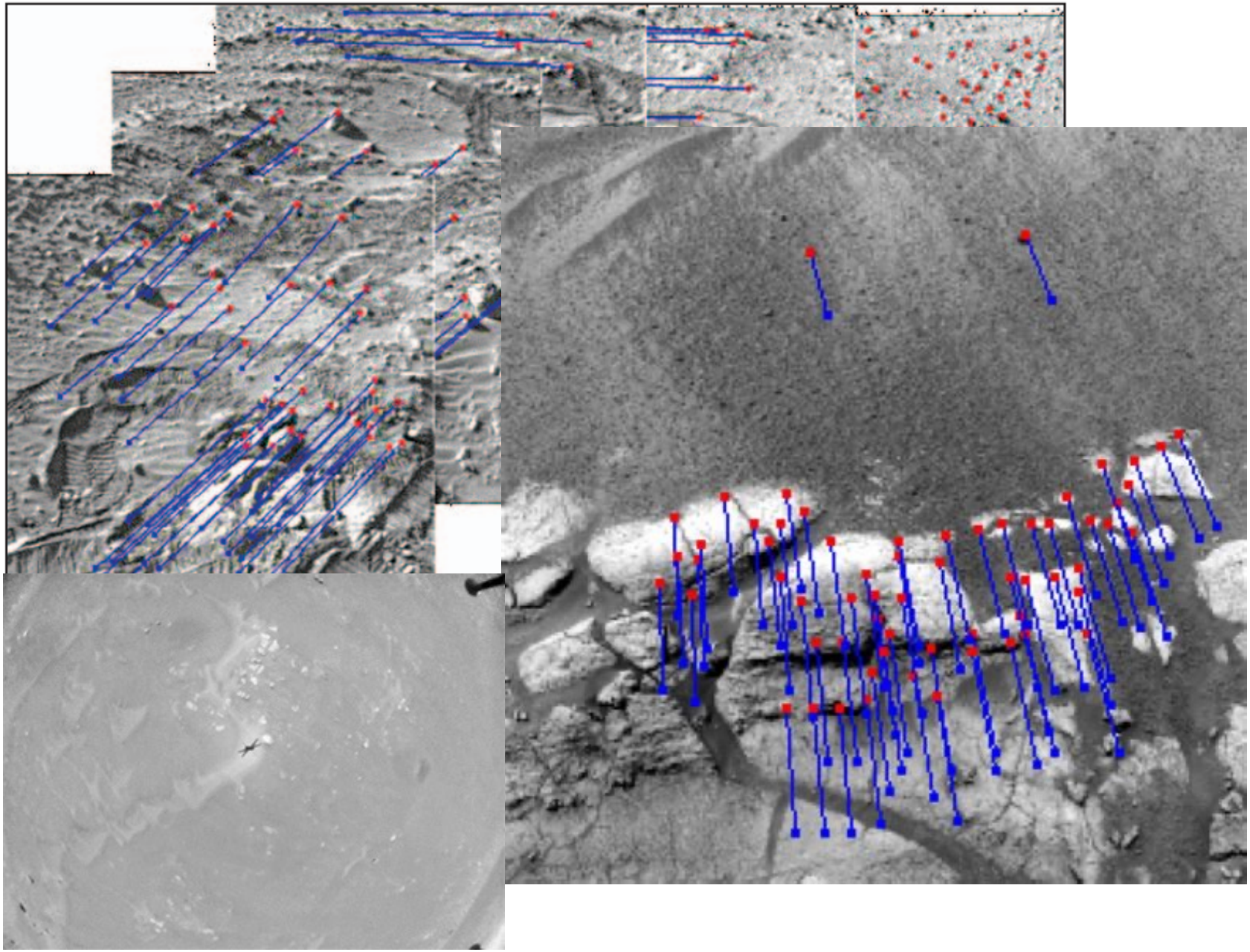
Visual odometry, or
Slip Check + “Auto”

Auto-navigation;
Geometric Hazard
Detection and
Avoidance

“Just wheel speeds”

“+check for slip”

“Self driving and mapping”



Driving Curiosity: Mars Rover Mobility Trends During the First Seven Years

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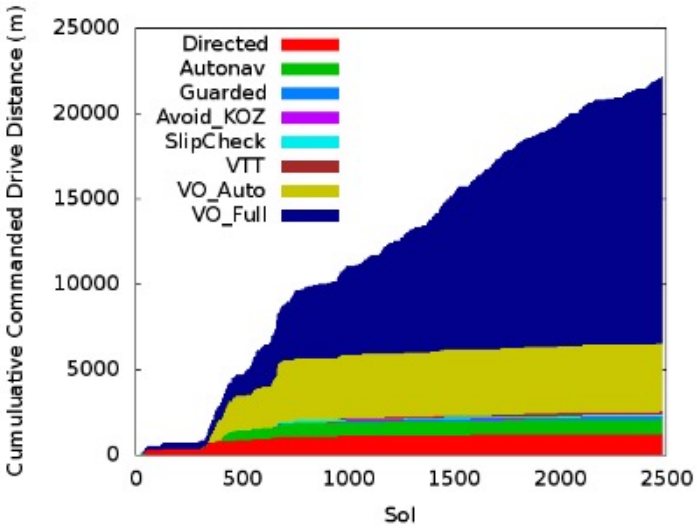
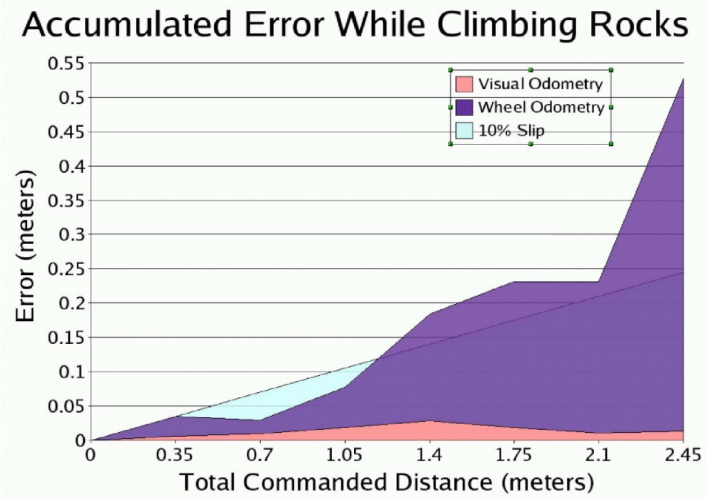




- Autonav is historically rare
- VO is really the only way to detect wheel slip or nav errors
- Yet still carries a 0.1-1.0% drift rate

Why 1% growth?

$$\hat{\boldsymbol{x}}_{k|k-1} = f(\hat{\boldsymbol{x}}_{k-1|k-1}, \boldsymbol{u}_k)$$
$$\boldsymbol{P}_{k|k-1} = \boldsymbol{F}_k \boldsymbol{P}_{k-1|k-1} \boldsymbol{F}_k^\top + \boldsymbol{Q}_k$$

$$\tilde{\boldsymbol{y}}_k = \boldsymbol{z}_k - h(\hat{\boldsymbol{x}}_{k|k-1})$$
$$\boldsymbol{S}_k = \boldsymbol{H}_k \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^\top + \boldsymbol{R}_k$$
$$\boldsymbol{K}_k = \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^\top \boldsymbol{S}_k^{-1}$$
$$\hat{\boldsymbol{x}}_{k|k} = \hat{\boldsymbol{x}}_{k|k-1} + \boldsymbol{K}_k \tilde{\boldsymbol{y}}_k$$
$$\boldsymbol{P}_{k|k} = (\boldsymbol{I} - \boldsymbol{K}_k \boldsymbol{H}_k) \boldsymbol{P}_{k|k-1}$$

It's "odometry" because you're continuously adding PSD matricies, meaning errors (eigenvalues) grow without bounds

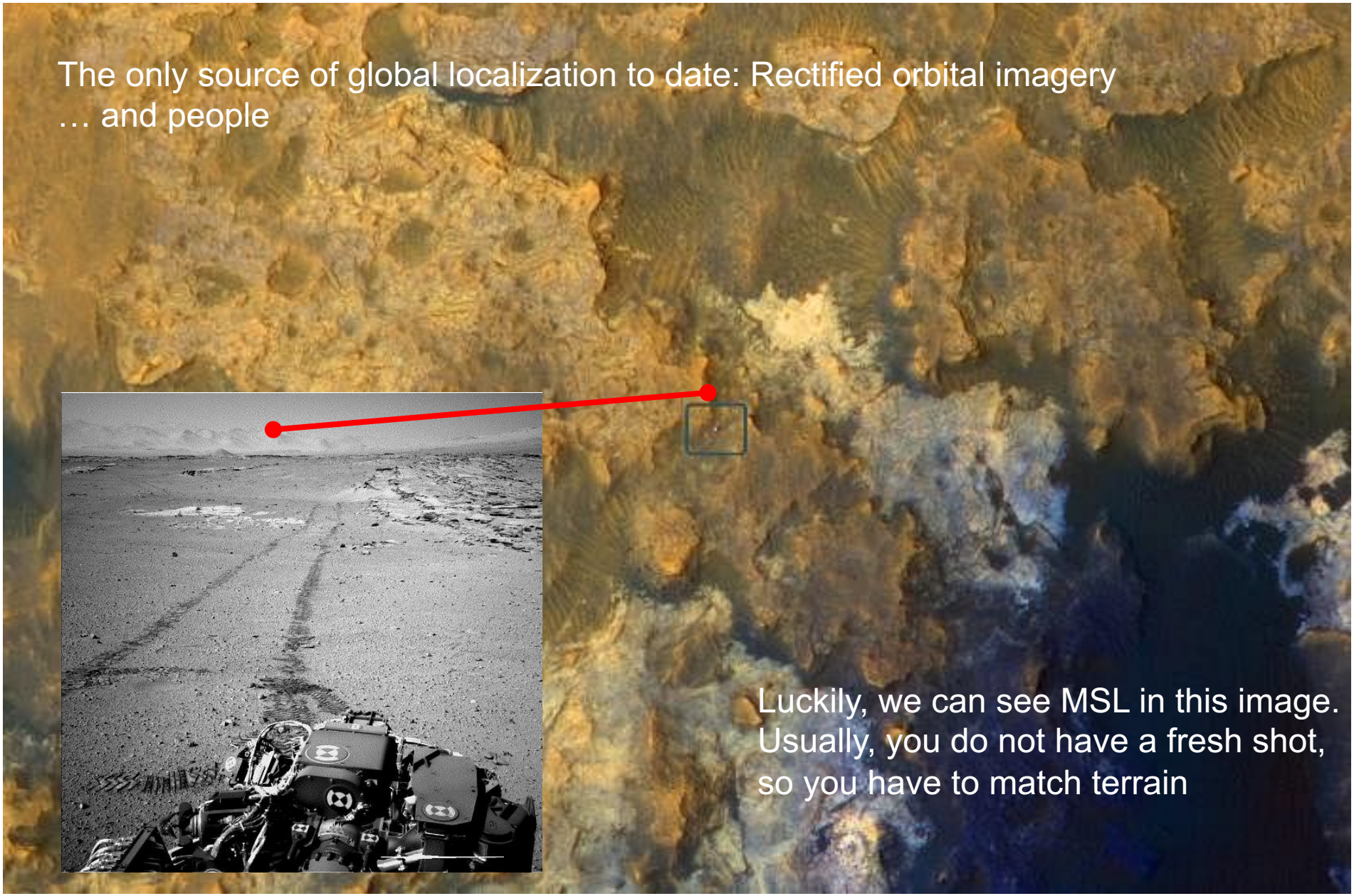
A rover cannot drill into a rock if it is 100m away from it after a day's drive.

Global Localization

ai.jpl.nasa.gov

Credit: https://yourstory.com/2015/07/vandi-verma-mars-curiosity/amp

Credit: https://yourstory.com/2015/07/vandi-verma-mars-curiosity/amp



Let’s automate that!

Topographical Landmarks for Ground-Level Terrain Relative Navigation on Mars

Joshua Vander Hook, Russell Schwartz, Kamak Ebadi, Kyle Coble, Curtis Padgett

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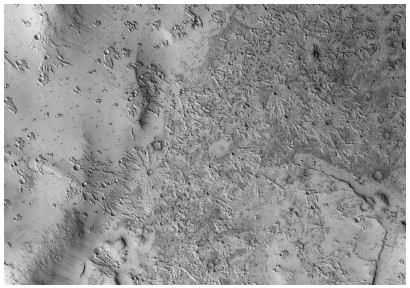
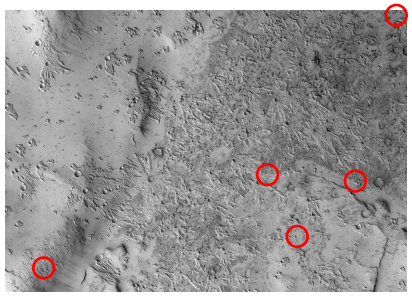
kwc57@cornell.edu, curtis.w.padgett@jpl.nasa.gov

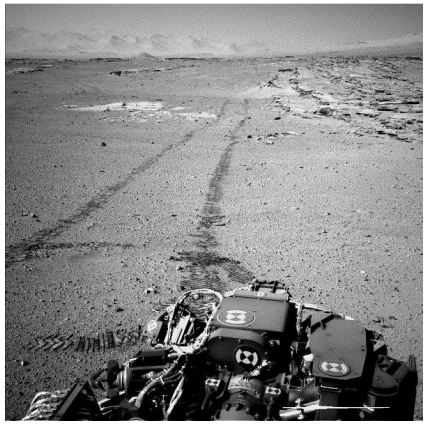
What if …



Take a global map

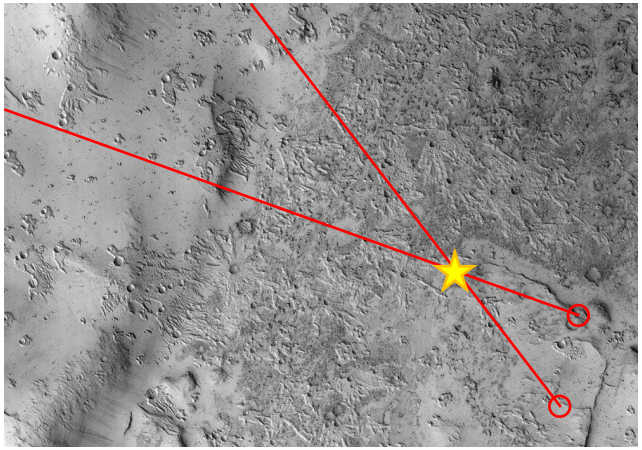


Find a bunch of peaks



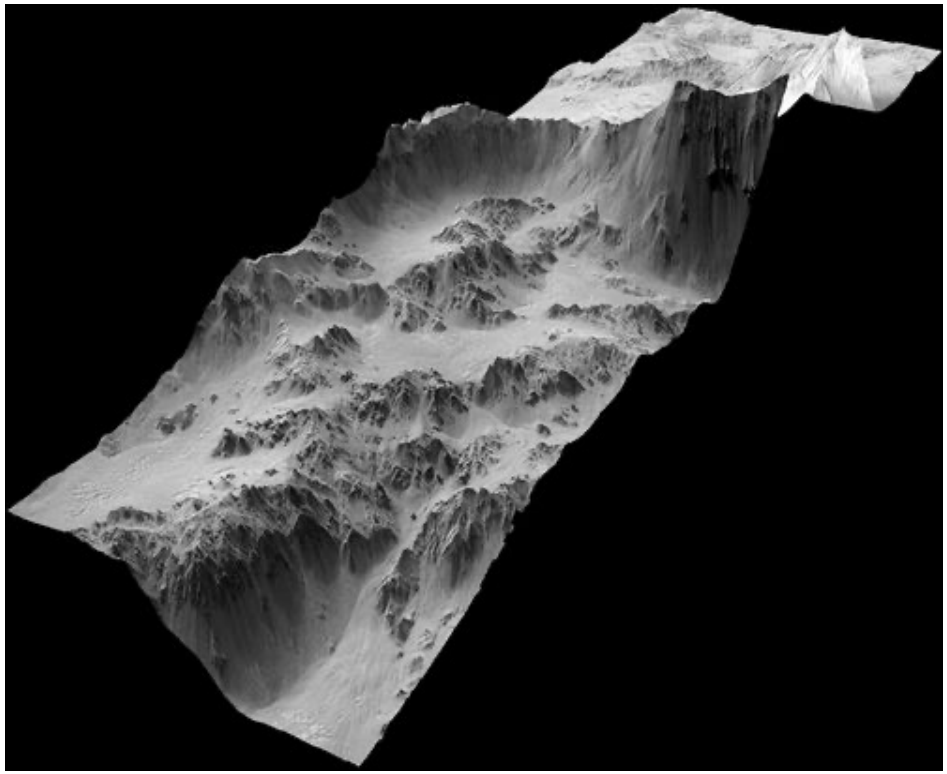
Take onboard images

And a few bearings

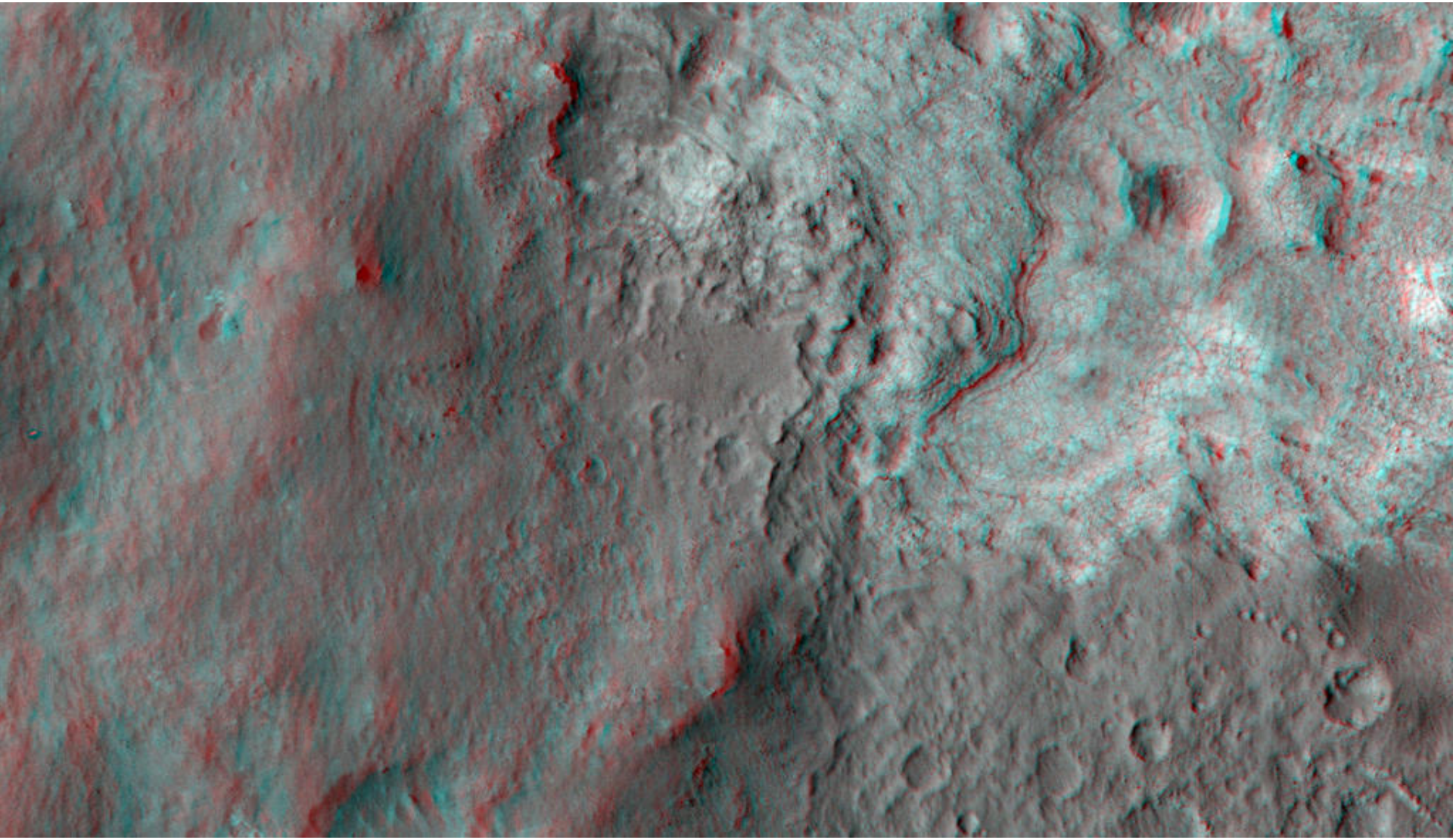


1. Global Map

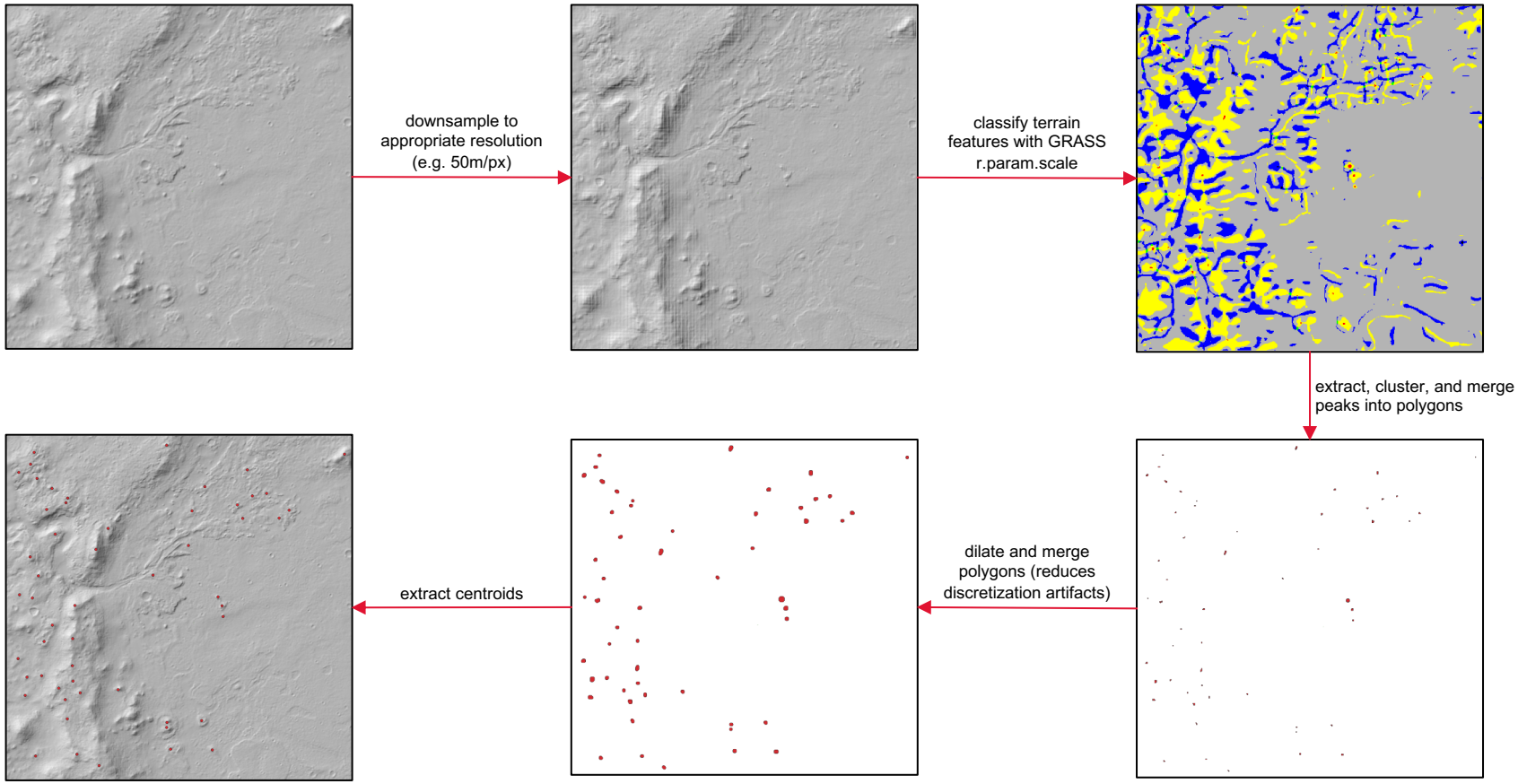
- Believe it or not, elevation maps for Mars exist and are fairly easy to find
- https://pds.jpl.nasa.gov/



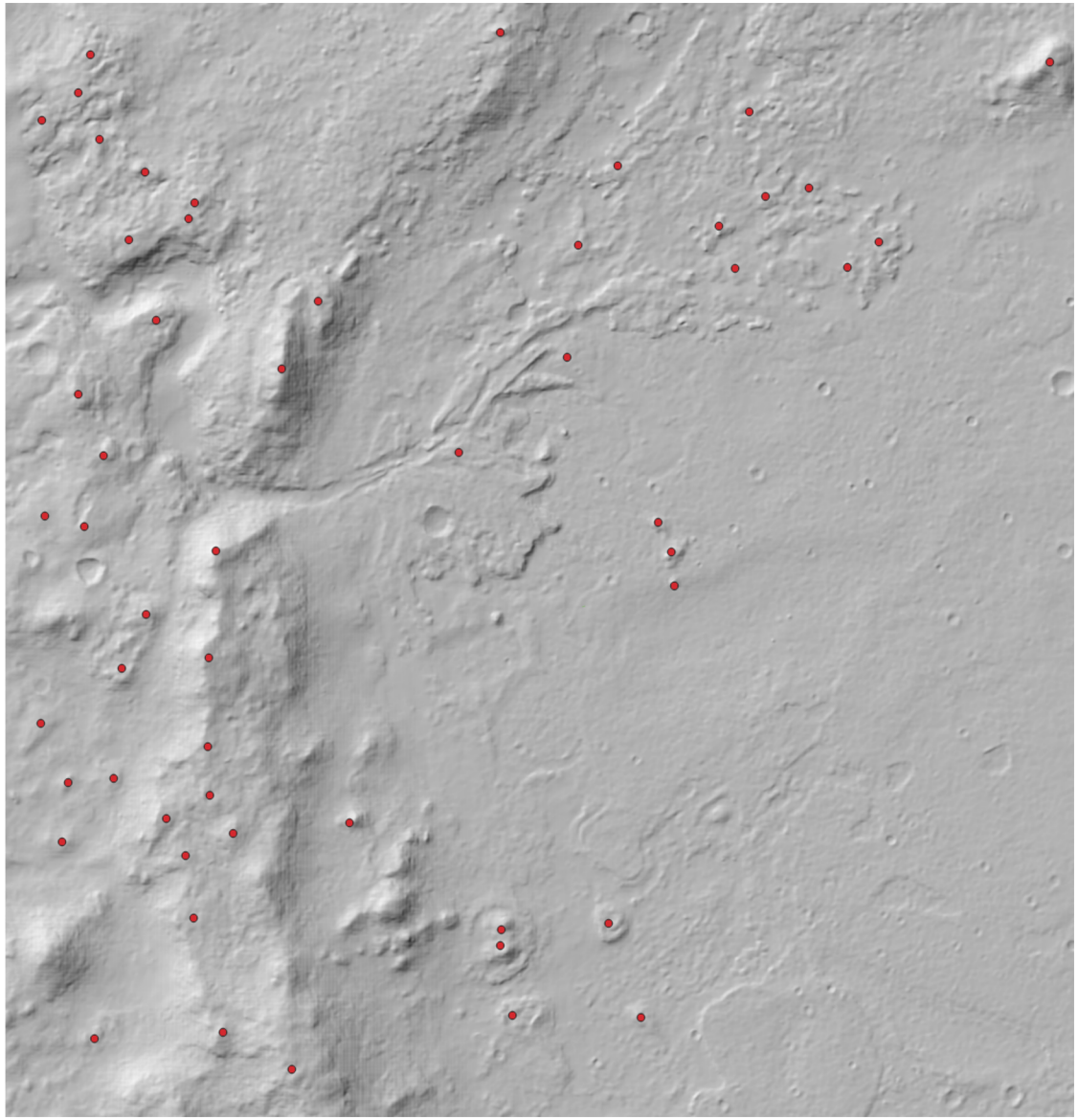
Credit: NASA/JPL



2. Find peaks

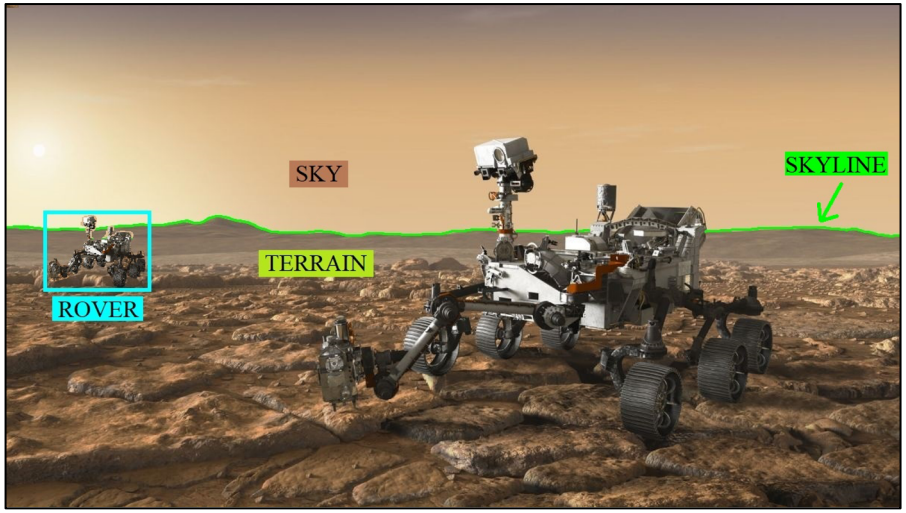


https://github.com/rschwa6308/Landmark-Based-TRN



3. Detecting Peaks in Rover Imagery

- Skyline delineation using semantic Segmentation for planetary robotic explorers (PERs)
- Demonstrate segmented skyline can be used for terrain relative navigation (TRN)
  - Compare to known Digital Elevation Model (DEM) data
- Semantic Segmentation using DeepLab V3+
  - Segment *terrain* from *sky*
- Method enables:
  - Monocular camera localization
    - > *Terrain Relative Navigation (TRN)*
    - > *GPS-denied areas*
  - Multi-agent operation
    - > *Cohort detection*



Toward Autonomous Localization of Planetary Robotic Explorers by Relying on Semantic Mapping

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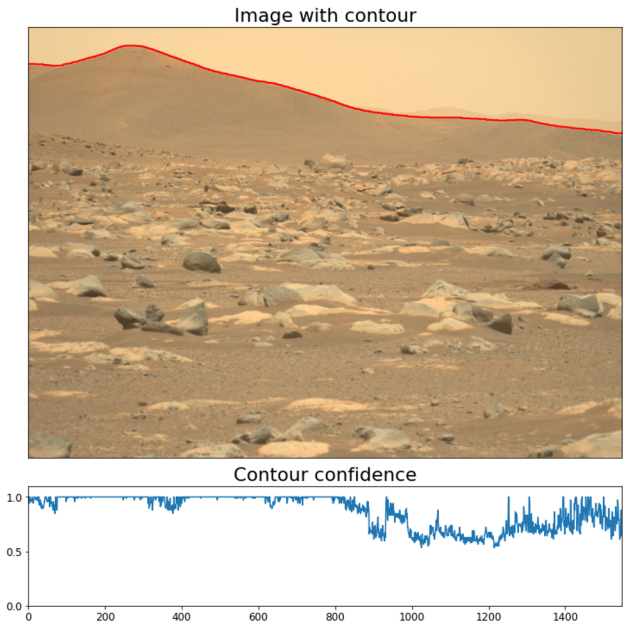
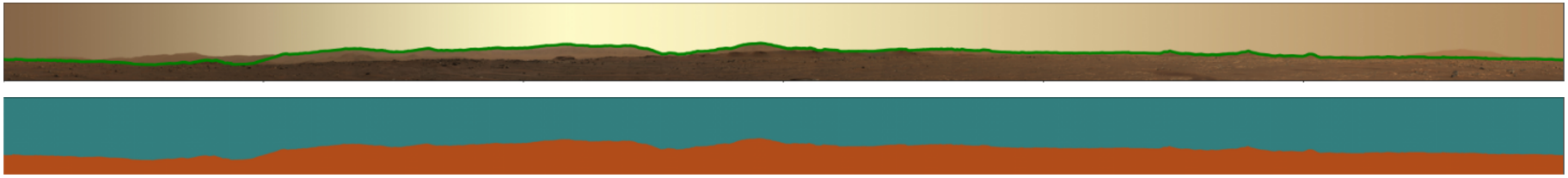
3. Detecting Peaks in Rover Imagery

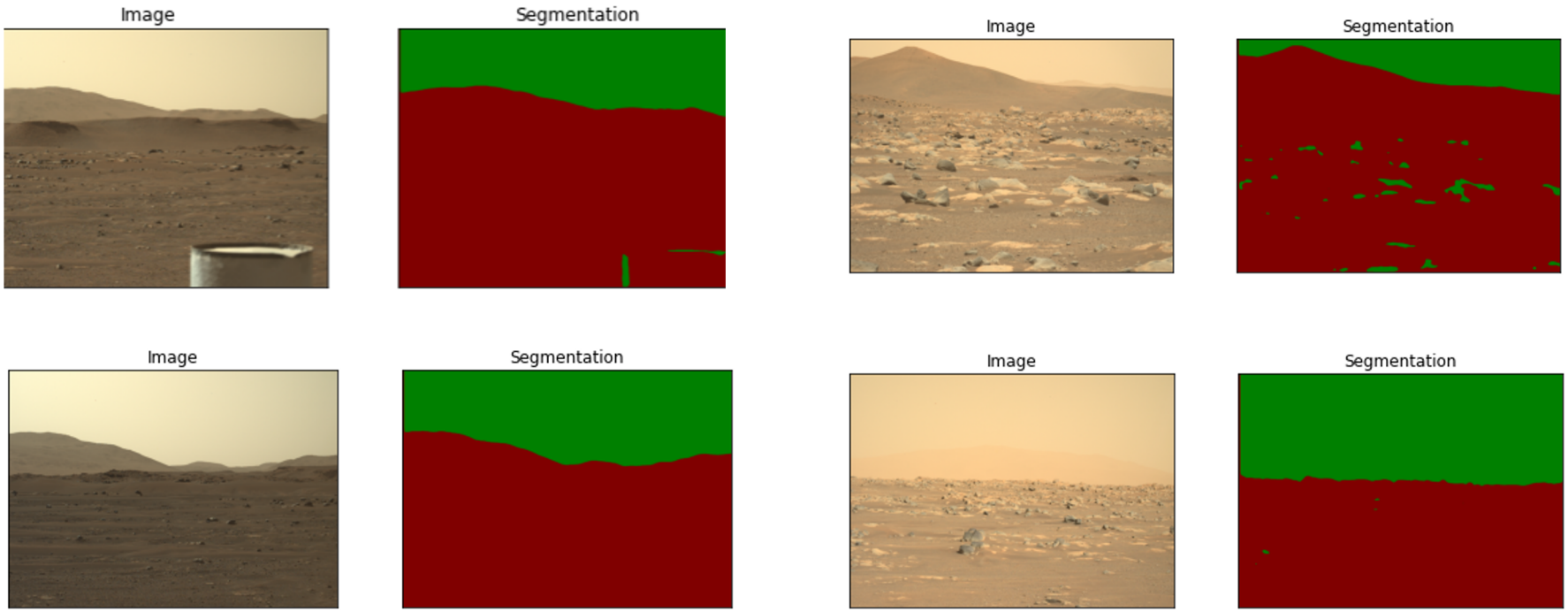
- Frameworks & Architectures:
  - DeepLab V3+ w/ MobileNet-V2 & Xception65
- Training | validation splits:
  - Mars: 20 train | 4 validations from Mars Curiosity Rover (PDS Image Atlas)
    - Two classes: ‘terrain’ and ‘sky’
    - Test set (experiments) comes from Mars Perseverance Rover
- Semantic labeling performed with labelme tool (https://github.com/wkentaro/labelme)
- Model used for experiments:
  - DeepLab V3+ with MobileNetV2 backbone, 750 training iterations w/ batch size: 2

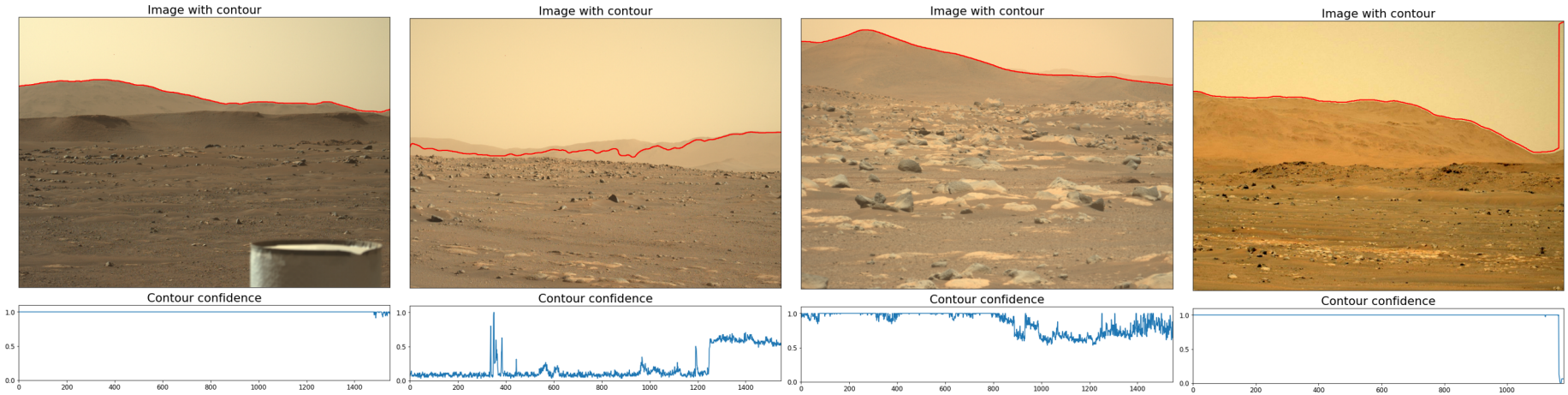




Semantic Segmentation Results

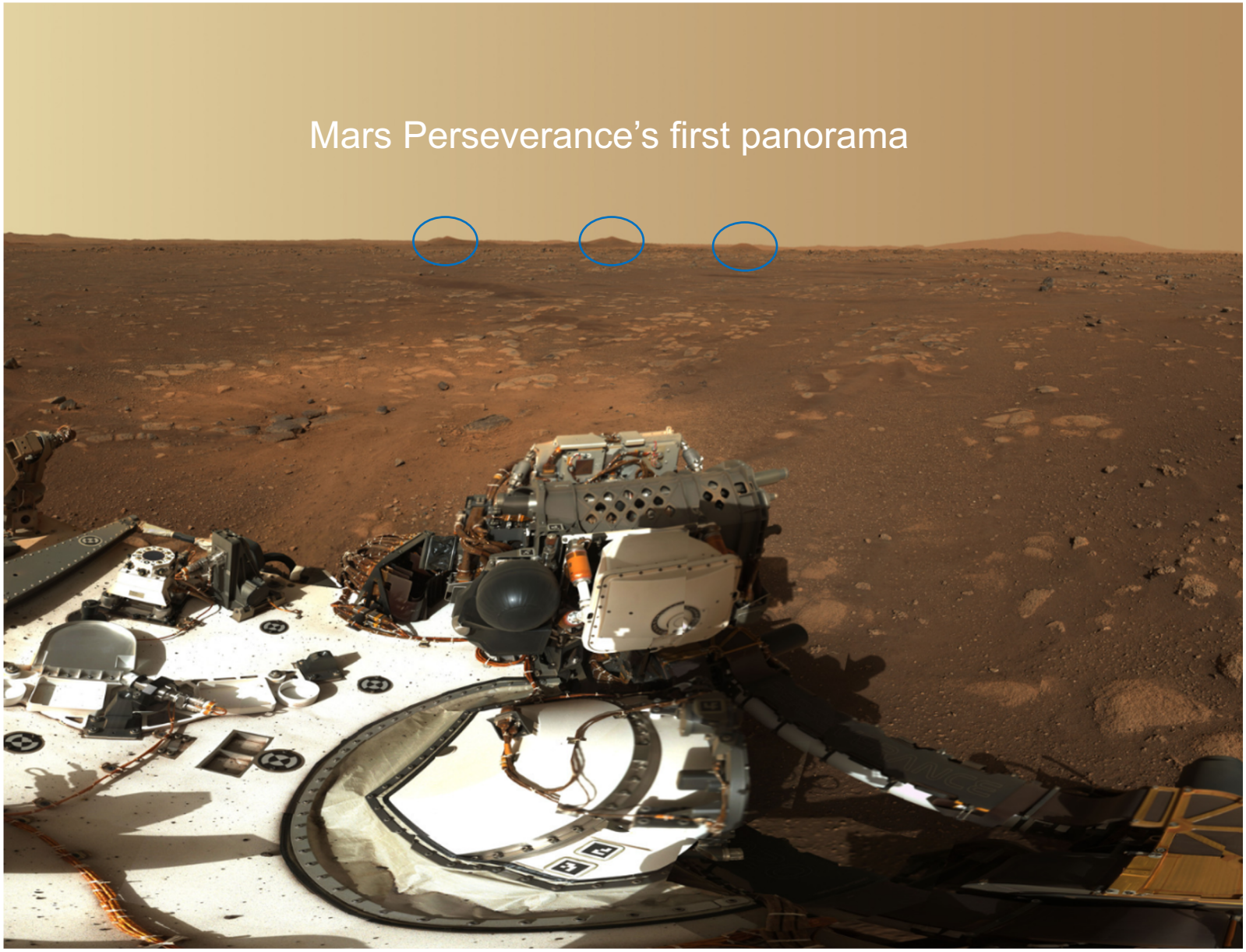
DeepLab V3+ MobileNetV2 @ 750 training iterations w/ batch size: 2
Inference time: 0.113 sec / image (on Colab GPU)

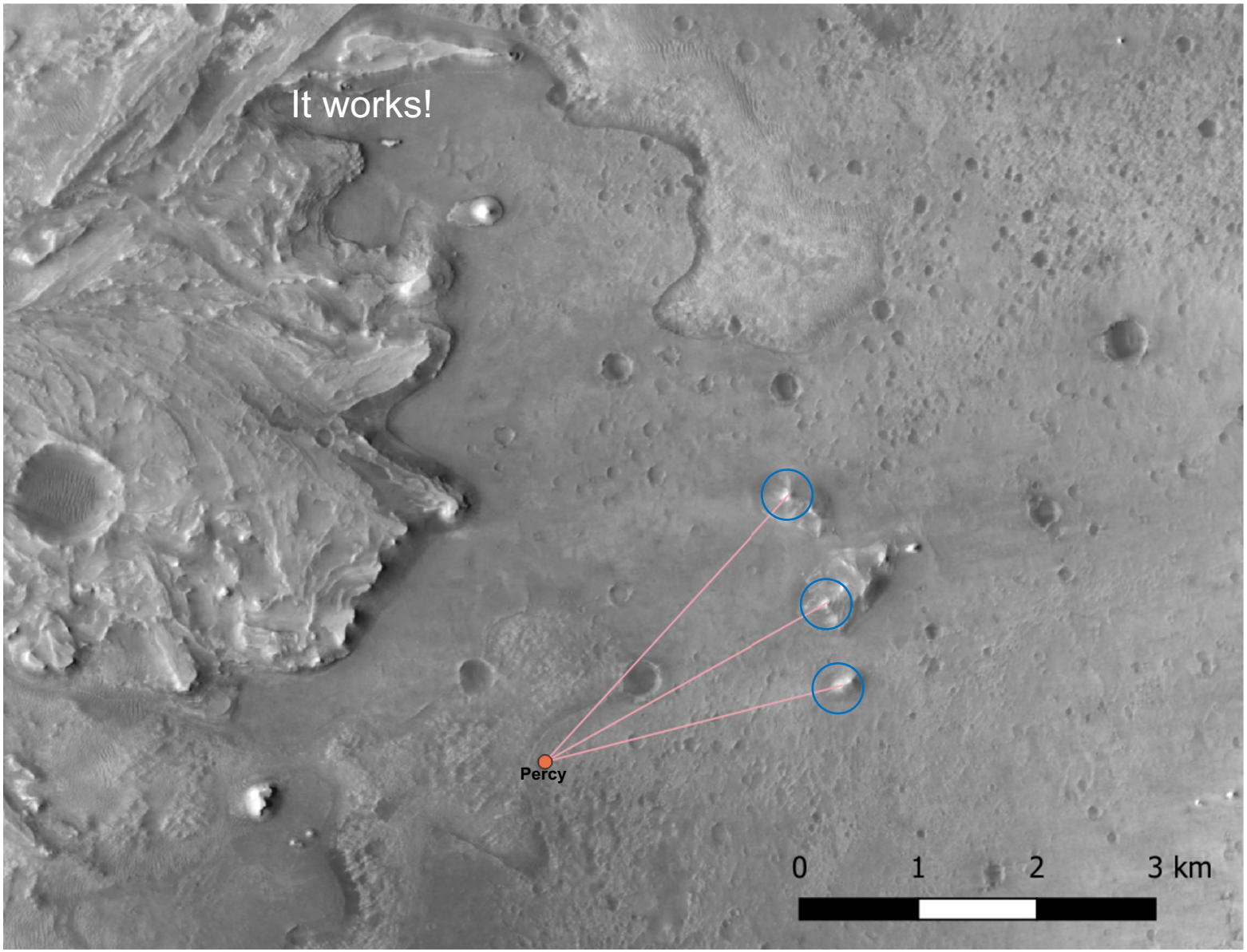




A fairly simple algorithm could isolate peaks from those contours

you can try it, see https://github.com/dkogan/horizonator
to render contours from elevation maps





Summary

- Given a map of known peak locations
- Take an onboard image and extract peaks from that image
  - (Take the machine learning course)
- Use the pixel coordinates to determine bearing to peak
  - (Take the computer vision course)
- Use bearings to estimate the rover's location on Mars

- Question: How *well* does this work? And when *won't* it work?

Estimating informativeness

- Suppose you know where you want to drive, but want to know if the rover could localize itself along that drive
- Or, suppose you wanted to know where to land so that you can get a quick nav fix

- We need an *informativeness* metric that includes:
  1. Rover's possible location
  2. Visibility of landmarks rover can use (visible/not visible)
  3. A cost function which rolls up the expected nav error given 1, 2

Hint: GDOP!

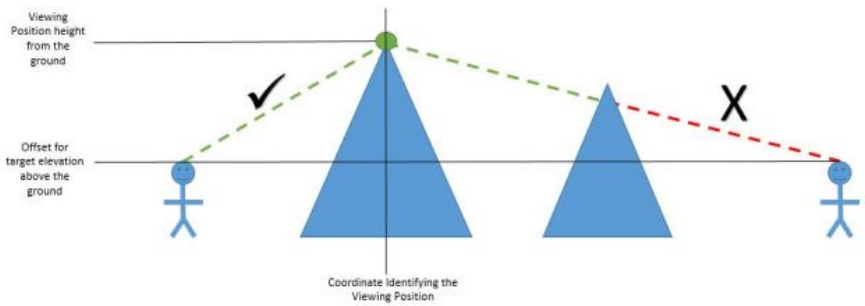
Estimating informativeness

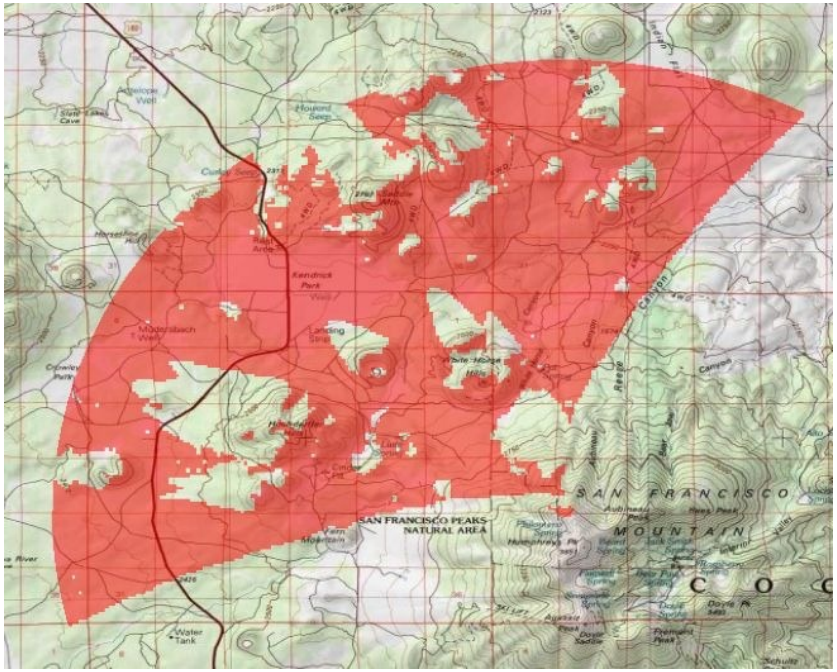
- Suppose you know where you want to drive, but want to know if the rover could localize itself along that drive
- Or, suppose you wanted to know where to land so that you can get a quick nav fix

- We need an *informativeness* metric that includes:
  1. ~~Rover's possible location~~ (Just use a whole area or trajectory)
  2. Visibility of landmarks rover can use (visible/not visible)
  3. A cost function which rolls up the expected nav error given 1, 2

2. Visibility of Landmarks

- Called the “viewshed”





- Geographic Information Systems (GIS) software like ArcGIS (right) and others will do this for you, given an elevation map
- We used QGIS https://www.qgis.org/en/site/

Deriving "informativeness"

EKF equations (Wikipedia)

$$\hat{\boldsymbol{x}}_{k|k-1} = f(\hat{\boldsymbol{x}}_{k-1|k-1}, \boldsymbol{u}_k)$$

$$\boldsymbol{P}_{k|k-1} = \boldsymbol{F}_k \boldsymbol{P}_{k-1|k-1} \boldsymbol{F}_k^\top + \boldsymbol{Q}_k$$

$$\tilde{\boldsymbol{y}}_k = \boldsymbol{z}_k - h(\hat{\boldsymbol{x}}_{k|k-1})$$

$$\boldsymbol{S}_k = \boldsymbol{H}_k \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^\top + \boldsymbol{R}_k$$

$$\boldsymbol{K}_k = \boldsymbol{P}_{k|k-1} \boldsymbol{H}_k^\top \boldsymbol{S}_k^{-1}$$

$$\hat{\boldsymbol{x}}_{k|k} = \hat{\boldsymbol{x}}_{k|k-1} + \boldsymbol{K}_k \tilde{\boldsymbol{y}}_k$$

$$\boldsymbol{P}_{k|k} = (\boldsymbol{I} - \boldsymbol{K}_k \boldsymbol{H}_k) \boldsymbol{P}_{k|k-1}$$

$$P_+ = (I - KH)P$$

(insert K, S definitions)

$$P_+ = P - PH^T(HPH^T + R)^{-1}HP$$

(Apply Matrix Inversion Lemma)

$$P_+ = (P^{-1} + H^T R^{-1} H)^{-1}$$

$$P_+^{-1} = P^{-1} + H^T R^{-1} H$$

Just add one 2x2 matrix for each peak to get new covariance

https://robotics.stackexchange.com/questions/1180/information-filter-instead-of-kalman-filter-approach/1185#1185

3. Informativeness of observations

If you know where the rover is (or could be), you can estimate the terms of the sum from the peaks that are visible …

We derive the “priorless” **covariance ellipse** centered on our true position, which shows the distribution of errors that any decent filter will have.

This is called

Geometric Dilution of Precision (**GDOP**)

Fisher Information

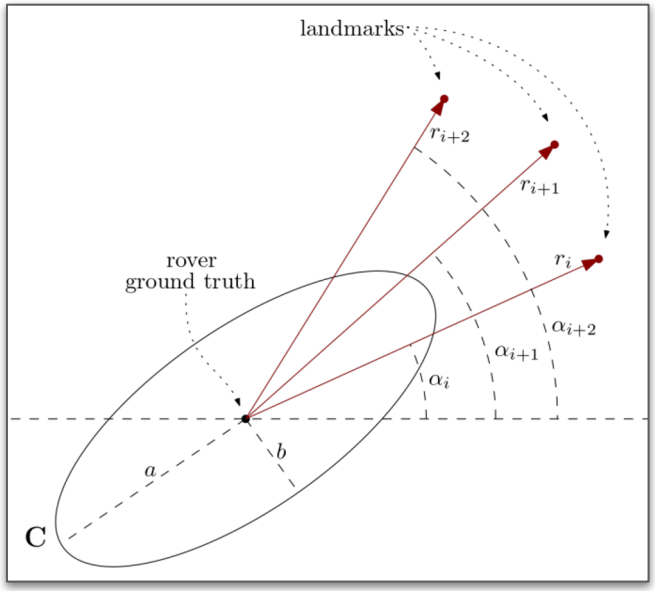
Cramer-Rao Lower Bound

For reference, typical GDOP for GPS is ~10 meters.

From previous slide, and assume no prior

$$P_+^{-1} = \cancel{P}^{-1} + H^T R^{-1} H$$

$$\mathbb{C}^{-1} = \sum_{i=1}^{N} \frac{1}{r_i^2 \sigma^2} \begin{bmatrix} \sin^2 \alpha_i & -\sin \alpha_i \cos \alpha_i \\ -\sin \alpha_i \cos \alpha_i & \cos^2 \alpha_i \end{bmatrix}$$



3. Informativeness of observations

Start with a digital elevation map (DEM) of the region in question.

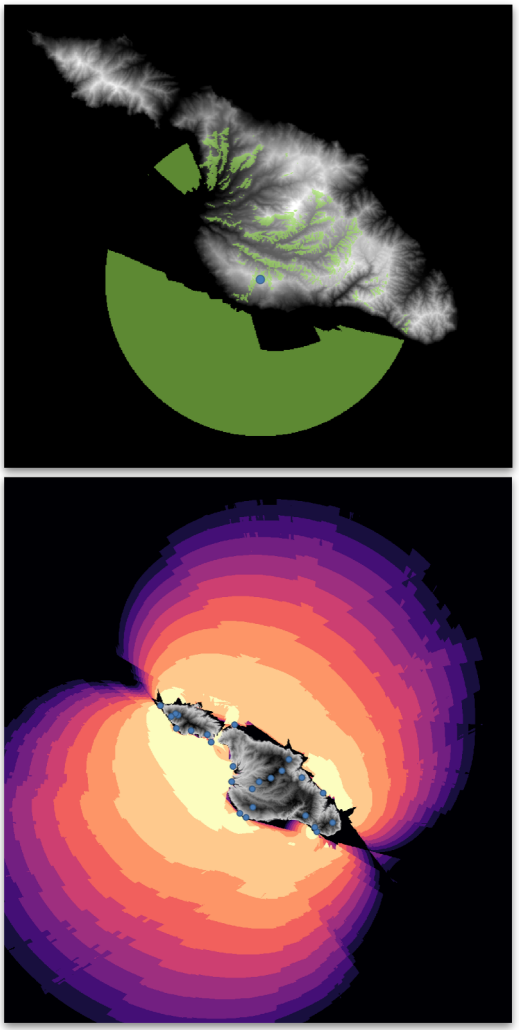
Extract peaks on that map

For each point on the map

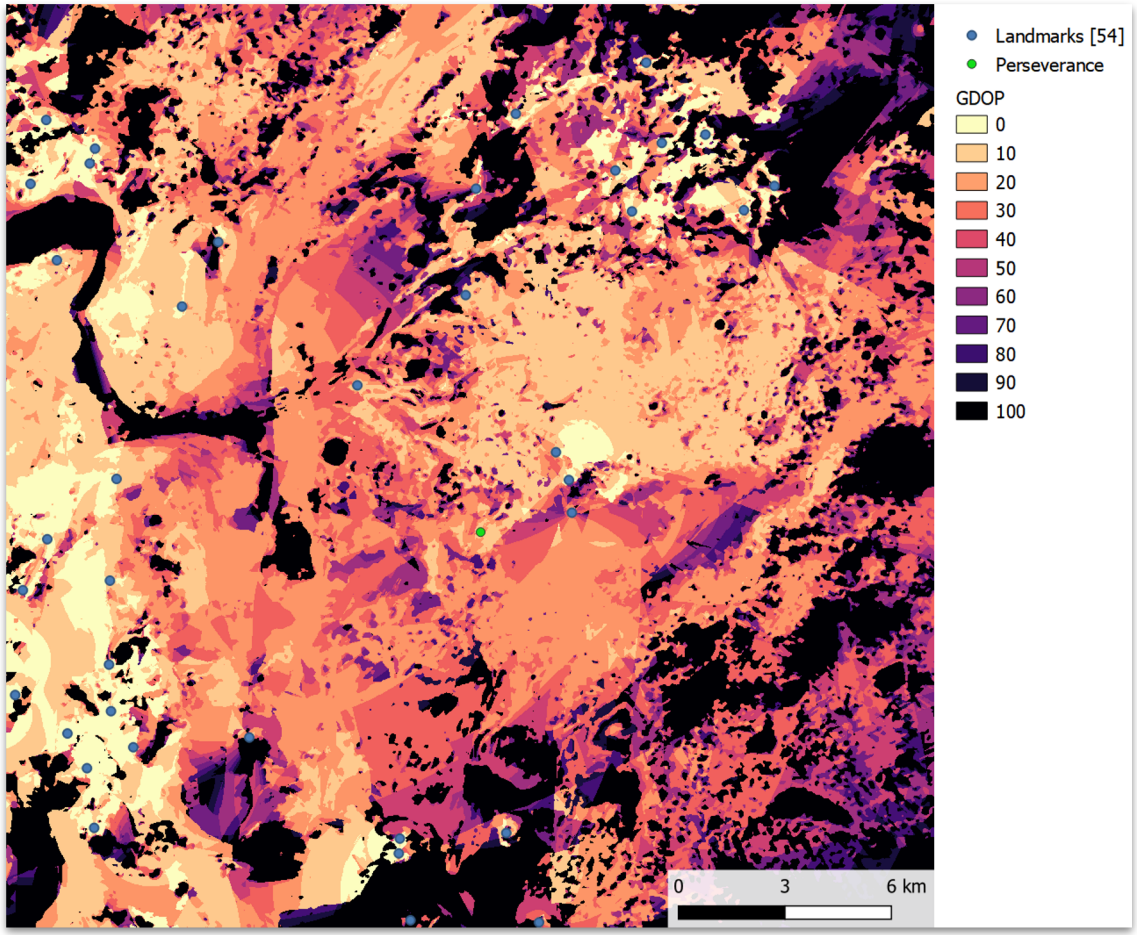
- Calculate which peaks are visible
- Calculate bearings to the peaks
- Plug into CRLB/GDOP

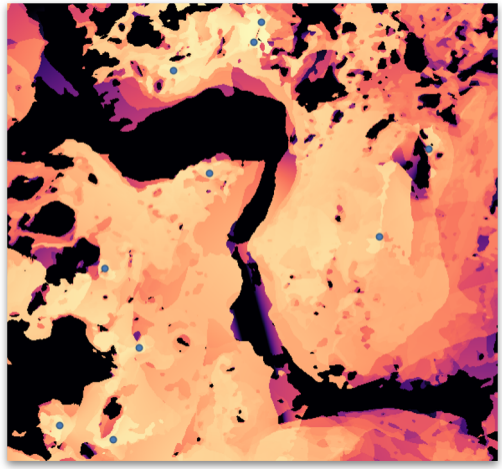
We developed a set of processing plugins for **QGIS** which automate this process.

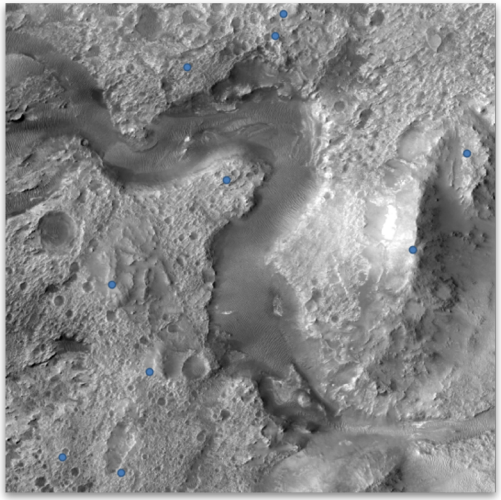
Example Right: Catalina Island.
Note that NW/SE is “bad” because the peaks are colinear, and that in general closer is better.



Informative locations in Jezero Crater







Parting

ai.jpl.nasa.gov
ml.jpl.nasa.gov
dus.jpl.nasa.gov

josh.vanderhook.info/talks

JPL is a diverse place, with people of all backgrounds and walks of life

We support a huge variety of projects, including Defense, Science, and Exploration of the Earth and Solar System

The AI Group(s) needs grads with:

- **Computer Science**
- Software engineering
- Combinatorial optimization
- Algorithm design & analysis
- *ML not required*
- TS/SCI clearance helpful for some projects!

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

credits

- https://www.youtube.com/watch?v=E3xWCqPBUFU
- https://www.youtube.com/watch?v=5qqsMjy8Rx0
- https://trs.jpl.nasa.gov/bitstream/handle/2014/47704/CL%2317-1496.pdf?sequence=1