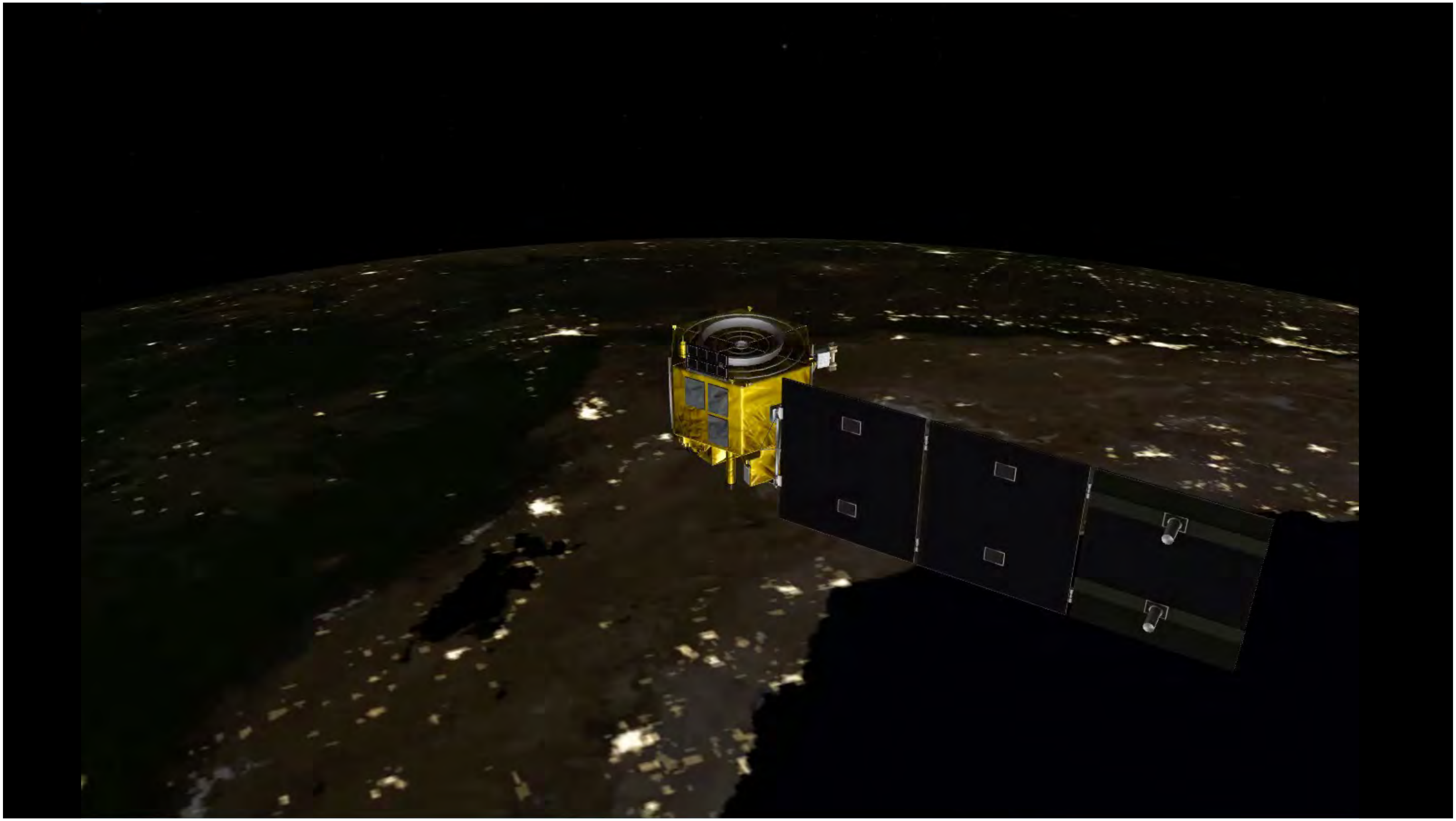
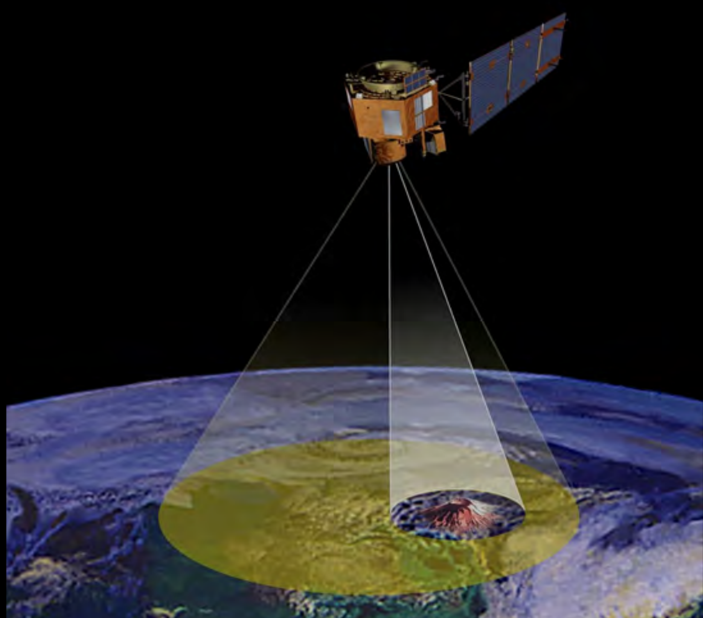
Artificial Intelligence in Space and the Hunt for life beyond Earth!

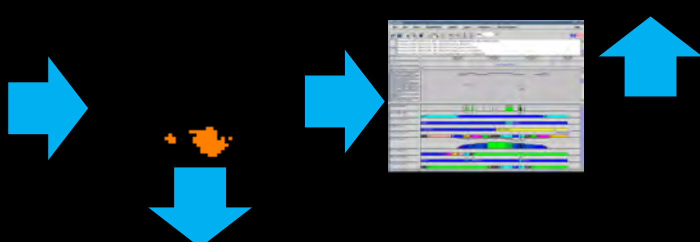
Steve Chien
Jet Propulsion Laboratory
California Institute of Technology
ai.jpl.nasa.gov ml.jpl.nasa.gov dus.jpl.nasa.gov

Portions of this work were carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
JPL Clearance: CL 23-4639.



The Autonomous Sciencecraft on Earth Observing One



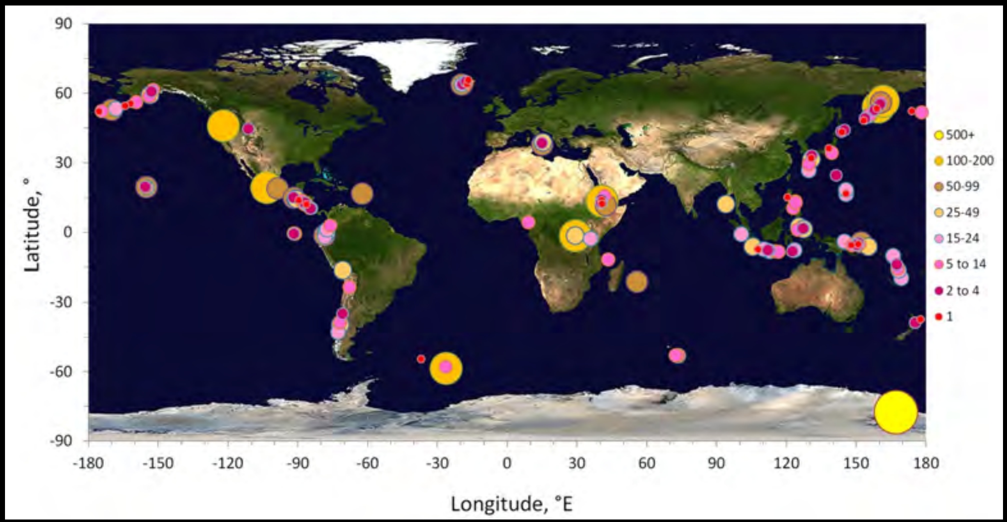


- 2004-2017 Primary Operations
- 60000+ autonomous data collects over 12+ years
  - ~ 3 M commands!
- Operations cost reduction > $1M/yr
- Reduce re-planning time to respond to anomalies from: days → hours
- (2009) R5 upgrade enabled significant increase in scene acquisition rate of ~ +33%
  - Estimated added value $800K+ / year
- ASE co-winner NASA Software of the Year 2005

POC: Steve Chien/JPL
https://ai.jpl.nasa.gov/public/projects/ase/

Example: NASA ASE/EO-1 Volcanoes

- Automated tasking: Volcano Sensorweb
  - Links together scores of space, ground, other assets
  - Automated Data analysis, triage to generate prioritized requests → ASE/EO-1 service → products delivered to stakeholders.
  - Over 100,000 alerts/triggers
    End Result, - Thousands of volcanic scenes 2008-2017,
    35%+ of said scenes with thermal signatures!
    Compare to MODIS background < 1% of scenes with active thermal signature.



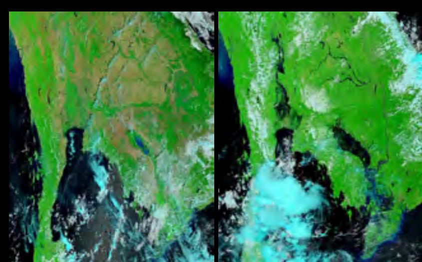
Partners (incomplete list):
MODVOLC
GOESVOLC
VIIRS (NPOES)
AFWA
VAAC
Iceland/MEVO
Etna VO (U. Firenze)
MEVO (NM Tech)
HVO (Kilauea)
IEGPN (Ecuador)
CVO (Mount St. Helens)

See [Chien et al. 2020 JAIS]
https://ai.jpl.nasa.gov/public/projects/sensorweb/

Example: NASA ASE/EO-1 Flooding

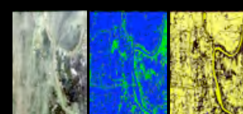
- Automated tasking: Thailand Flood Sensorweb
  - Links together space, ground assets
  - Automated Data analysis, triage to generate prioritized requests
    → ASE/EO-1observation service and others
    → products to stakeholders
  - Fuse data from satellite, ground sensor, and model sources

+100% temporal coverage for 2010-2011, 2011-2012 Flooding Seasons

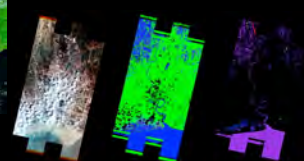


Dry: March 6, 2011

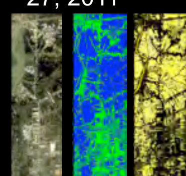
Flooded: October 27, 2011



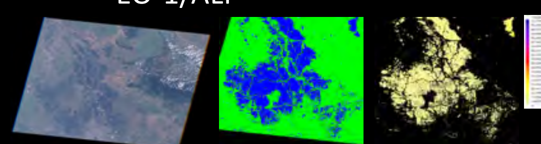
GeoEye-1



EO-1/ALI



Ikonos



Landsat-7 ETM

In-situ data and Model

Partners:
HAII (Thailand)
Digital Globe (Worldview)
Geo-Eye
Radarsat
Landsat
LANCE-MODIS

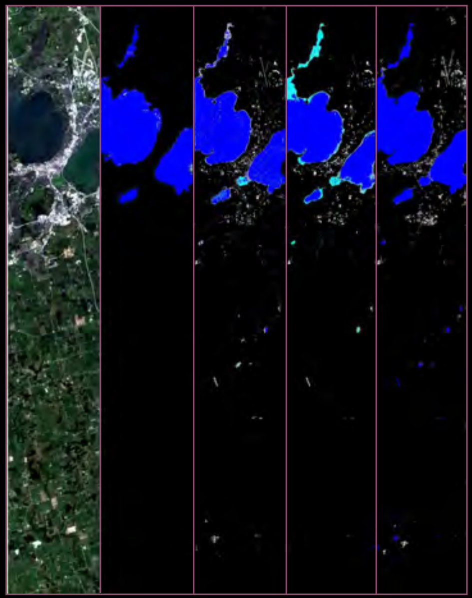
See [Chien et al. 2011 IGARSS, 2013 JSTARS].
See also Wildfires [Chien et al. 2011 JSTARS, Chien et al. JAIS 2018]

Land, Ice, Water, Snow Detection using Support Vector Machines

- Primary Purpose
  - Identify areas of land cover (land, ice, water, snow) in a scene
- Three algorithms:
  - Scientist manually derived
  - Automatic best ratio
  - Support Vector Machine (SVM)

Classifier	Expert Derived	Automated Ratio	SVM
cloud	45.7%	43.7%	58.5%
ice	60.1%	34.3%	80.4%
land	93.6%	94.7%	94.0%
snow	63.5%	90.4%	71.6%
water	84.2%	74.3%	89.1%
unclassified	45.7%		

Lake Mendota, Wisconsin

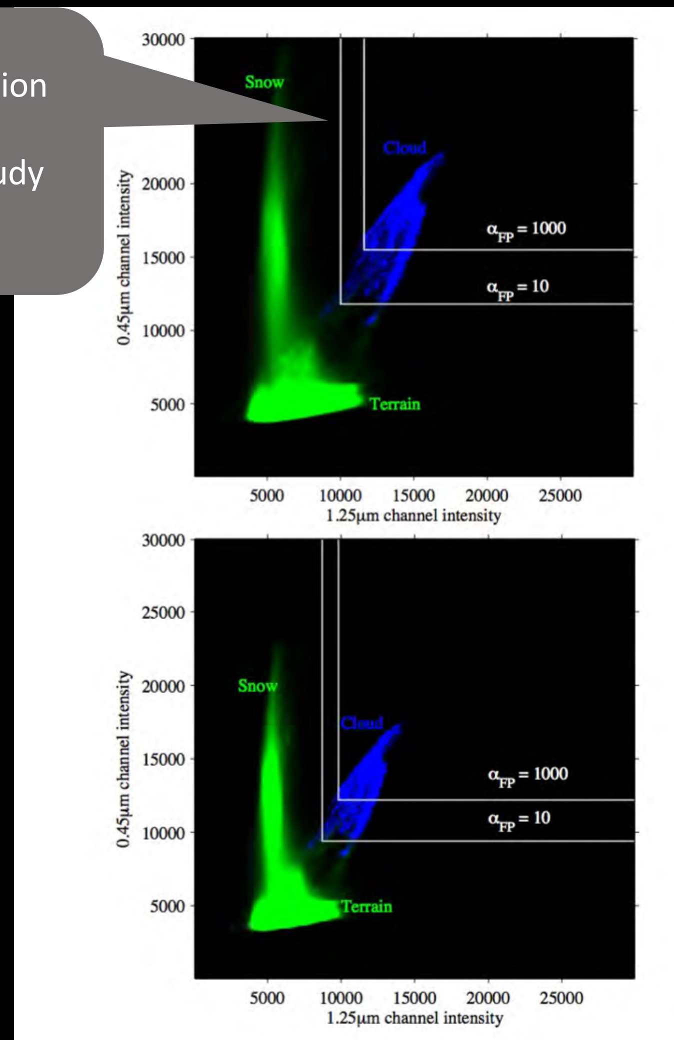


Visible Image | Expert Labeled | Expert Derived | Automated Ratio | SVM

T. Doggett et al. 2006 RSE

Bayesian Thresholding

Bayesian thresholding exploits the natural division between dark surface materials and bright cloudy regions at particular wavelengths.



- While the RDF method examines a window of values around the pixel to be classified, BT classifies each pixel independently.
- BT was previously employed to analyze data collected by the AVIRIS-C airborne sensor [Thompson et al. 2014].
- For EO- 1, BT used Hyperion bands at 447, 1245, and 1658 nm to span the range from blue to short-wave infrared.

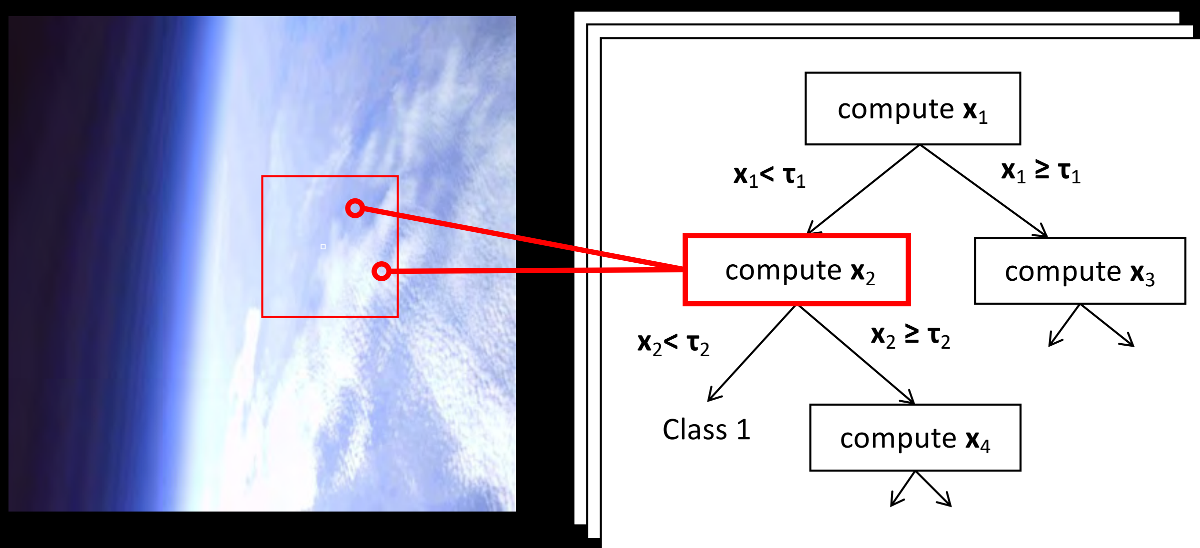
Image courtesy Thompson et al. 2014 TGARS

TextureCam – Random Decision Forests

Pixel classification for cloud screening,

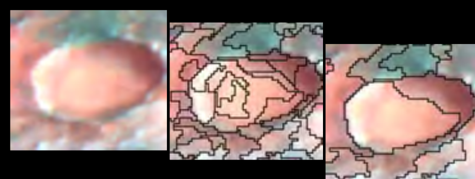
Pixel to be classified

Random forest classifier



[Thompson et al., i-SAIRAS 2012; Wagstaff et al., *GRL* 2013; Bekker et al., *Astrobiology* 2014]

Onboard Hyperspectral Analysis

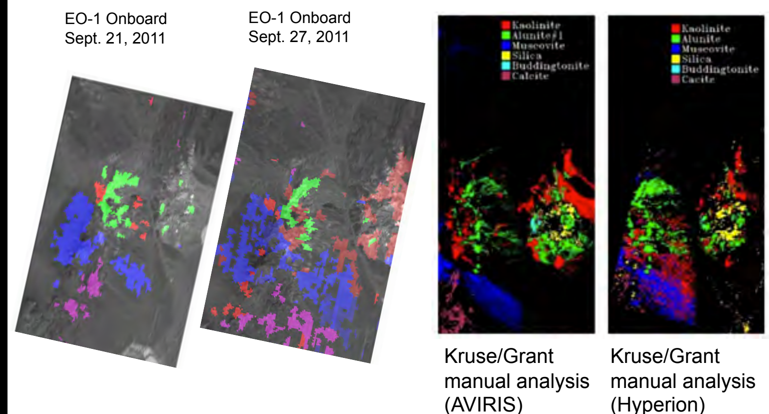


Superpixel segmentation
+
The sequential maximum angle convex cone (SMACC)
endmember extraction

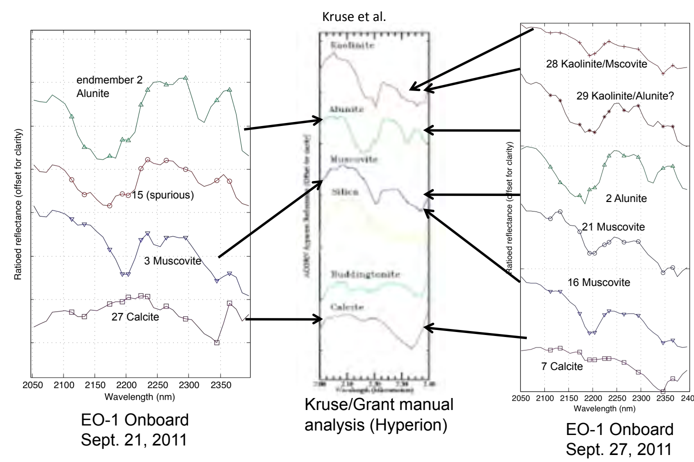
Results from onboard EO-1 (9/2011)

D. Thompson et al. 2012 TGARS

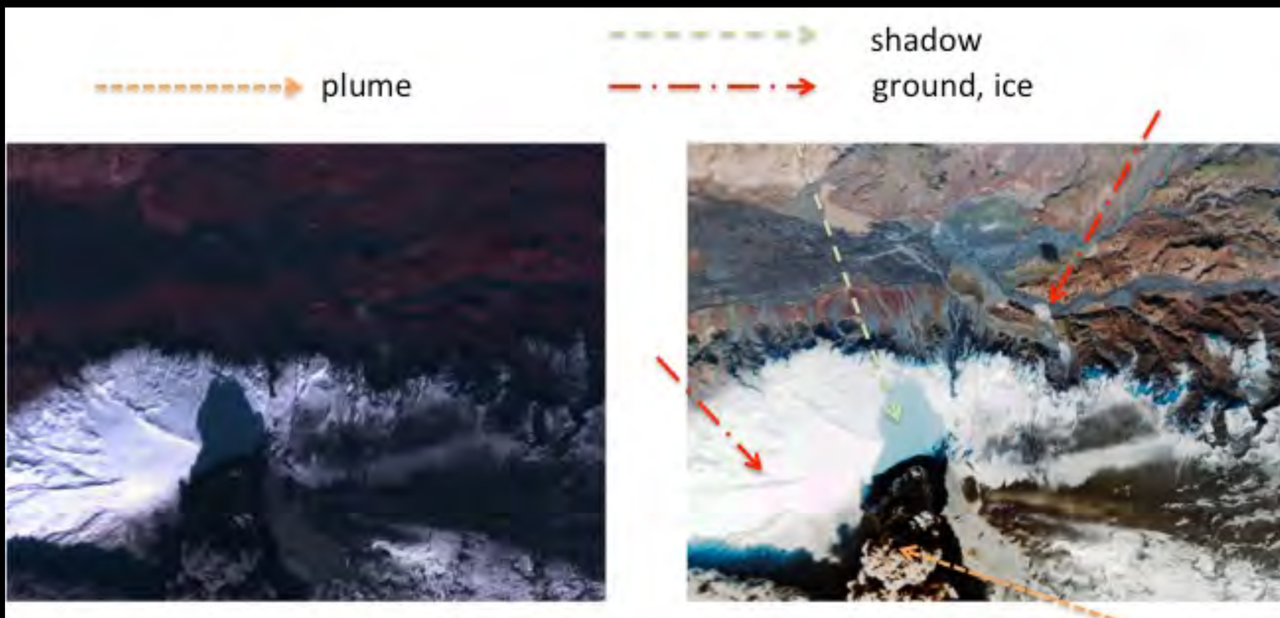
Repeatability: maps



Repeatability: detections



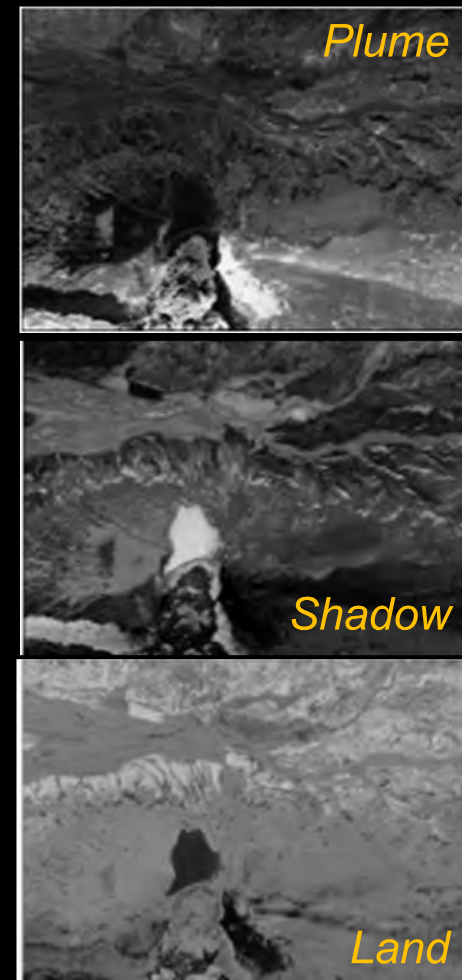
WorldView-2 Data



WorldView-2 Image of Eyjafjallajökull eruption, acquired April 17, 2010

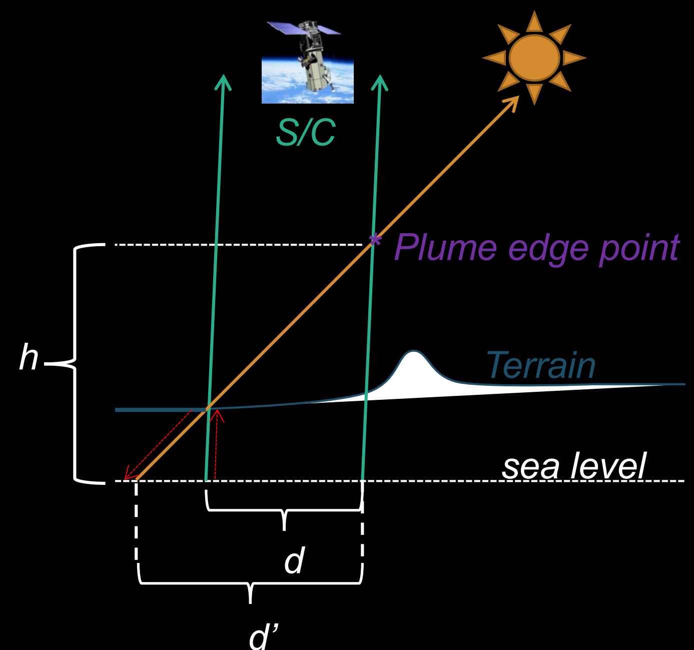
Histogram-equalized image

Mclaren et al. 2012, SPIE



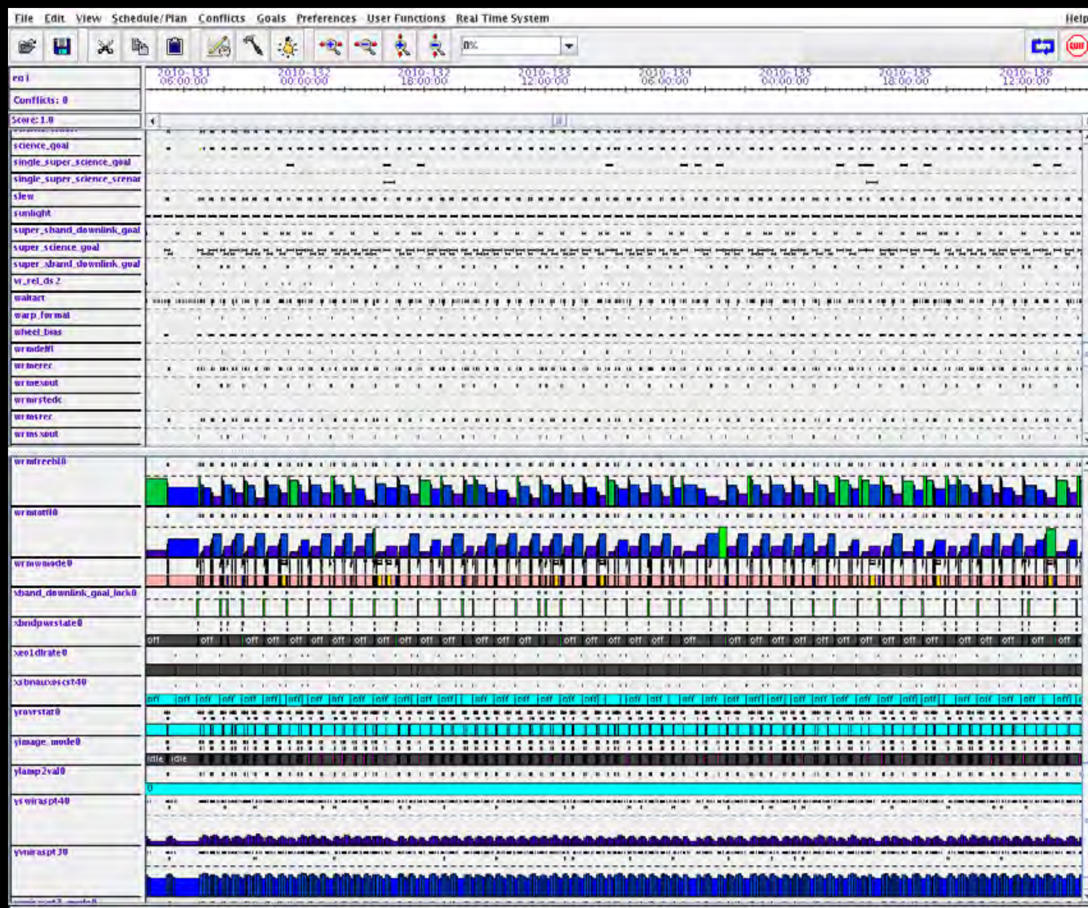
Height Estimation

- Estimate plume height from shadows
- Followed calculations derived in A. J. Prata and I. F. Grant, “Determination of mass loadings and plume heights of volcanic ash clouds from satellite data”
- Rotated classification maps so sun rays are coming from –Y axis (bottom of the image)
- Collected shadow line segments which have a neighboring plume region in sunward direction
- Corrected shadow lengths for:
  - Sun and spacecraft azimuth, elevation
  - Ground elevation at shadow edge
    - ASTER GDEM2 DEM
    - 30m horiz. spacing, 1m vert.



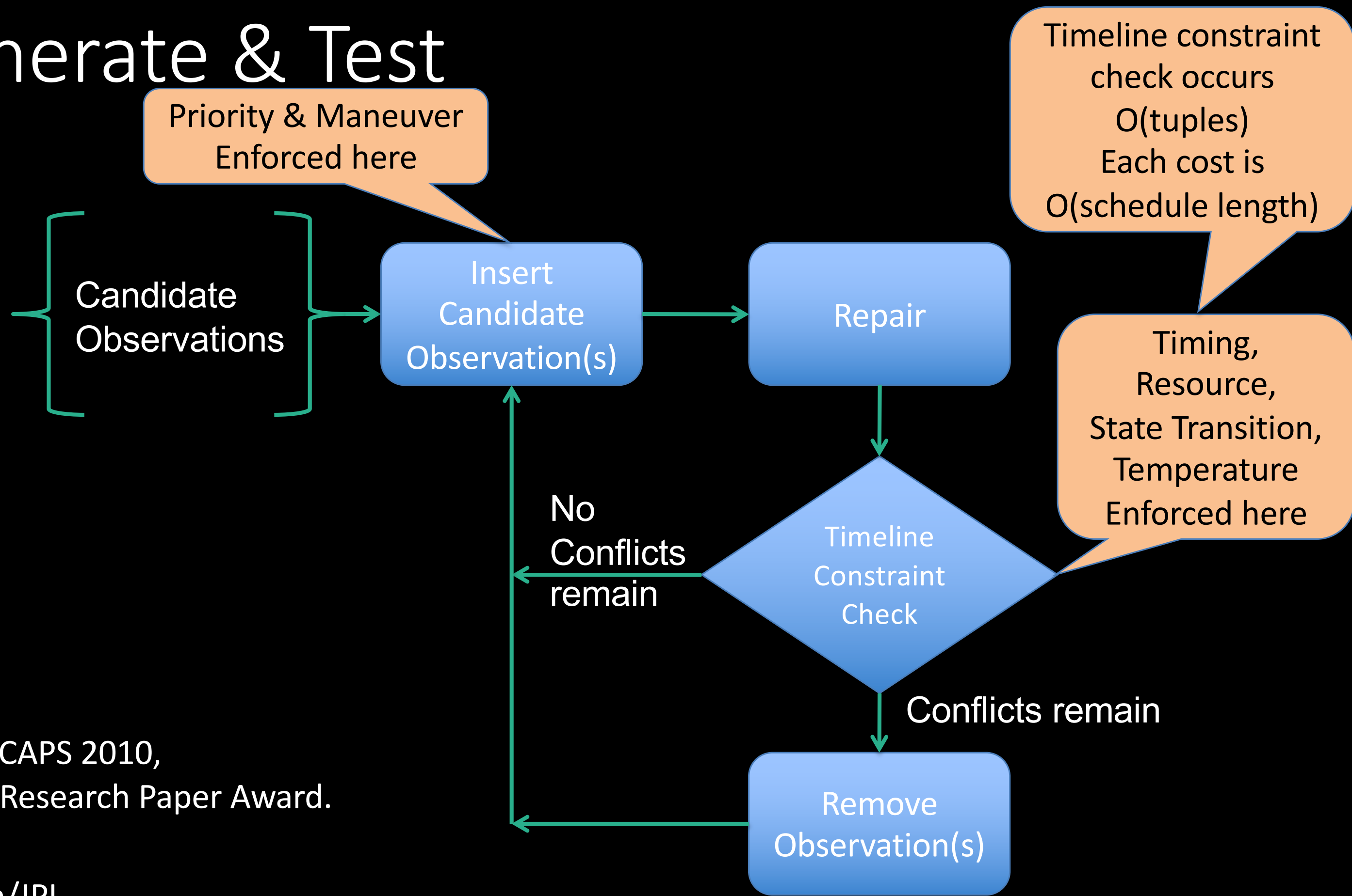
d *: Initial shadow length*
d’*: Shadow length after projecting up to DEM & down along sun vector*
h *: Plume point height*

Timeline-based Scheduling



Many timeline based schedulers in use for space missions.
See
[Chien et al. 2012, SpaceOps]

Generate & Test



See:
Chien et al., ICAPS 2010,
Best Applied Research Paper Award.

POC: S. Chien/JPL

WIRED

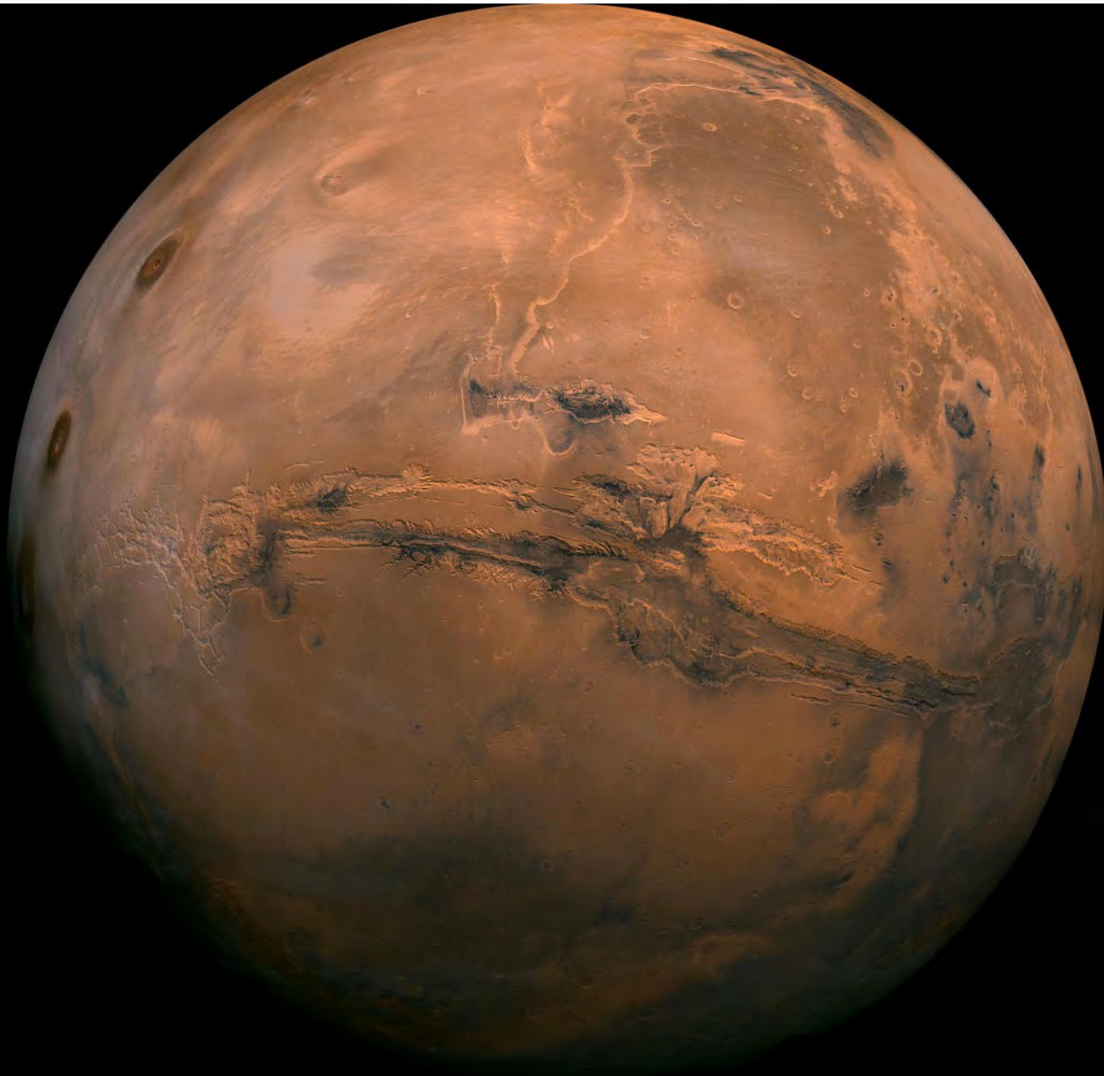
The Journey of NASA's Smartest Satellite Finally Comes to an End

SHARE

2337

Manam Volcano viewed from EO-1 on June 28th 2010 ALAMY

https://www.wired.com/2017/03/say-farewell-eo-1-nasas-smartest-satellite/



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ARS UNITE —

NASA's next Mars rover will use AI to be a better science partner

Experience gleaned from EO-1 satellite will help JPL build science smarts into next rover.

Enlarge / The Mars 2020 rover will likely carry artificial intelligence software to help manage the science workload.

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Welcome to Ars UNITE, our week-long virtual conference on the ways that innovation brings unusual pairings together. Each day this week from Wednesday through Friday, we're bringing you a pair of stories about facing the future. Today's focus is on AI in manufacturing and space—stand by to blast off!

NASA can't yet put a scientist on Mars. But in its next rover mission to the Red Planet, NASA's Jet Propulsion Laboratory is hoping to use artificial intelligence to at least put the equivalent of a talented research assistant there. Steve Chien, head of the AI Group at NASA JPL, envisions working with the Mars 2020 Rover "much more like [how] you would interact with a graduate student instead of a rover that you typically have to micromanage."

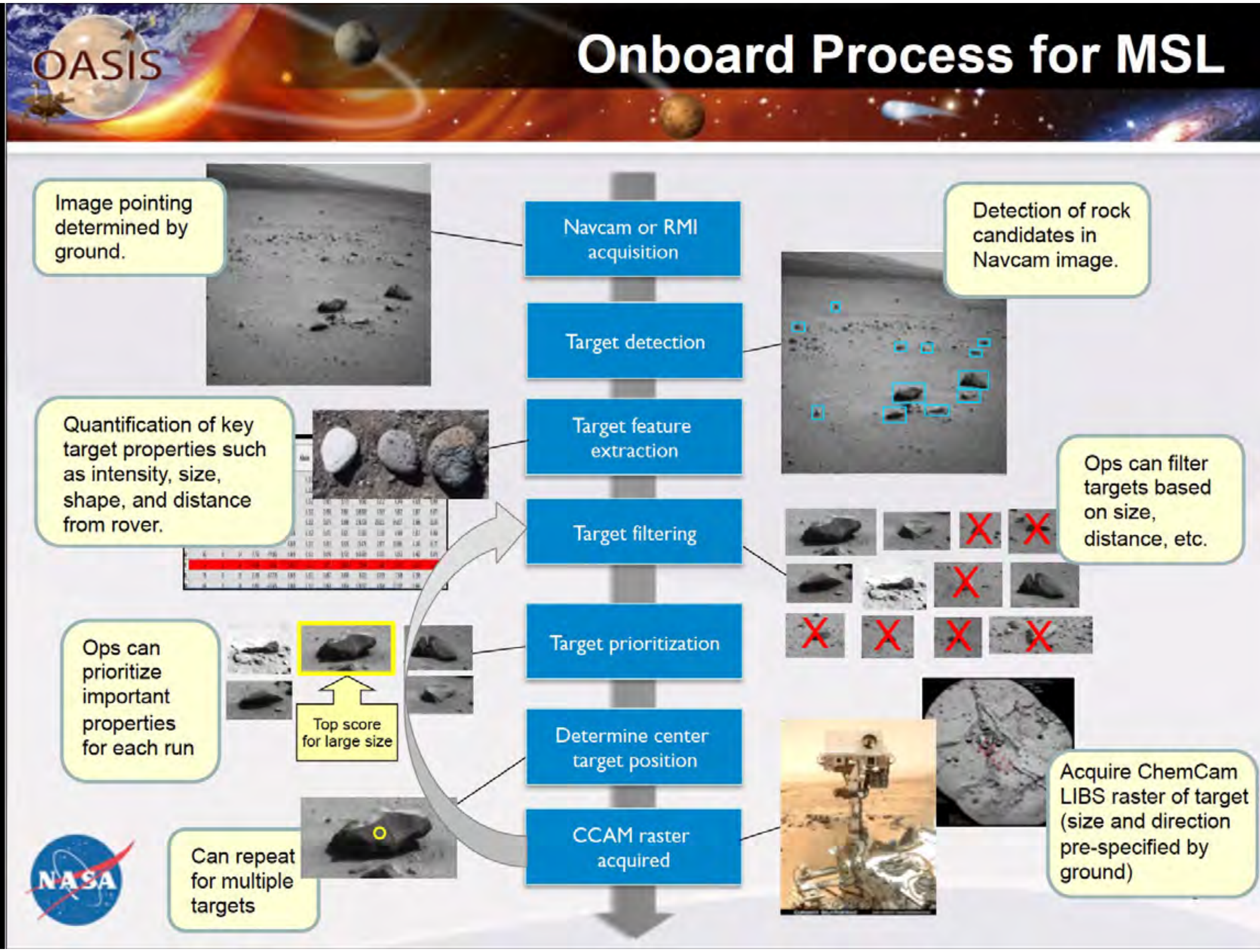
Ars Unite

Why driving is hard—even for AIs

All hail the AI overlord: Smart cities and the AI Internet of Things

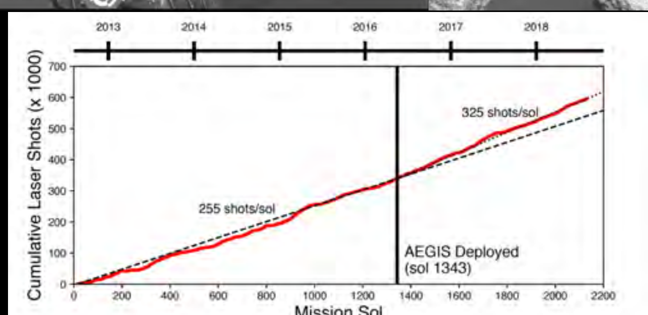
Predecisional, for planning and discussion only.


00:00:12

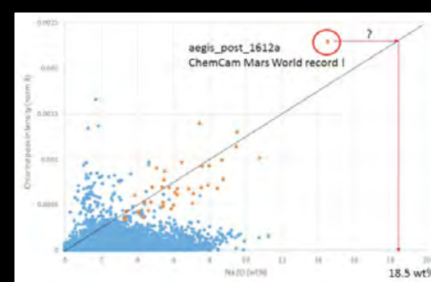


OASIS
Onboard Process for MSL
Image pointing determined by ground.
Navcam or RMI acquisition
Detection of rock candidates in Navcam image.
Target detection
Quantification of key target properties such as intensity, size, shape, and distance from rover.
Target feature extraction
Target filtering
Ops can filter targets based on size, distance, etc.
Ops can prioritize important properties for each run
Top score for large size
Target prioritization
Determine center target position
Acquire ChemCam LIBS raster of target (size and direction pre-specified by ground)
CCAM raster acquired
Can repeat for multiple targets
NASA

AEGIS Results on MSL Curiosity



Significant increase in rate of data return from ChemCam



Sol 1612: AEGIS found highest concentration of chlorine ever measured by ChemCam on Mars

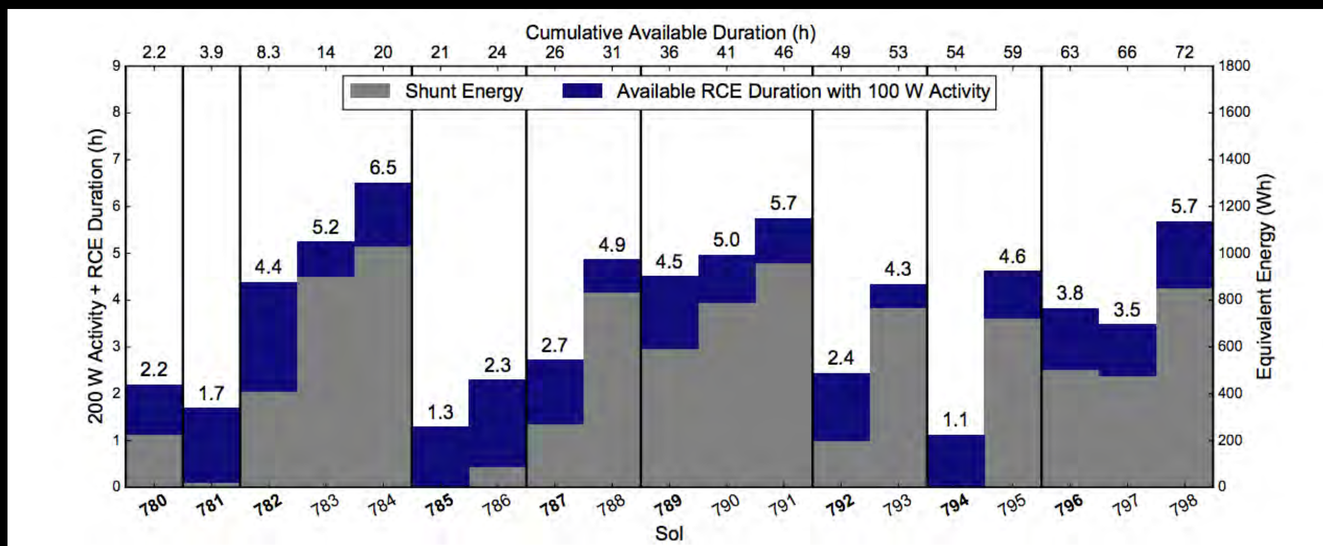
Targets Selected in First M2020 Run

SCAM and high-res Navcam data acquired on above two identified rock targets (Sol 383)

Sol 383 =
March 19, 2022

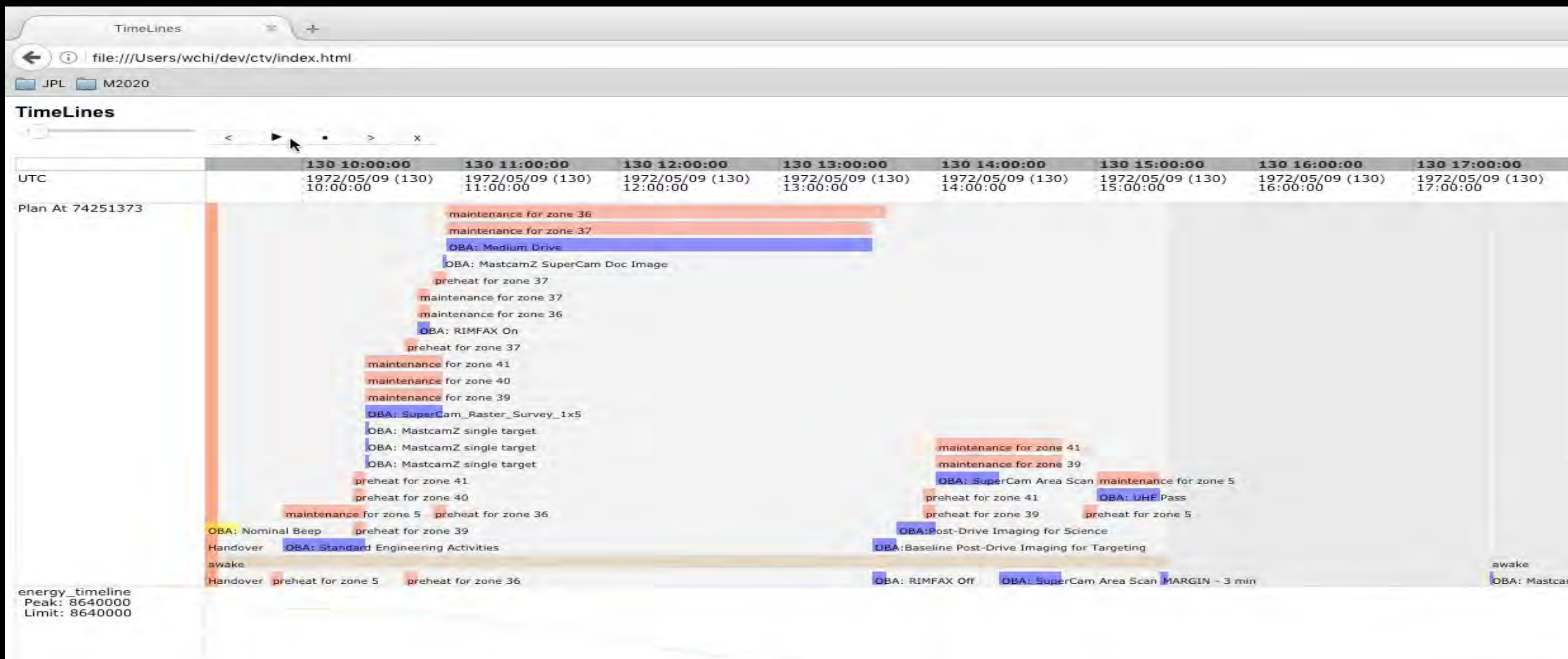
AEGIS POCs: Tara Estlin, Dan Gaines, Raymond Francis, Jet Propulsion Laboratory, California Institute of Technology

MSL unused Time/Energy



MSL submasters on average execution time 28% less than planned time (+ cleanups). [Gaines et al. 2016]

Example M2020 Sol Type:
Medium Drive with post drive imaging.



Rabideau et al. 2017 IWPSS; Chi et al 2018 ICAPS; Chi et al. 2019 ICAPS; Chi et al. 2020 ICAPS

POC: D. Gaines, S. Kuhn, S. Chien

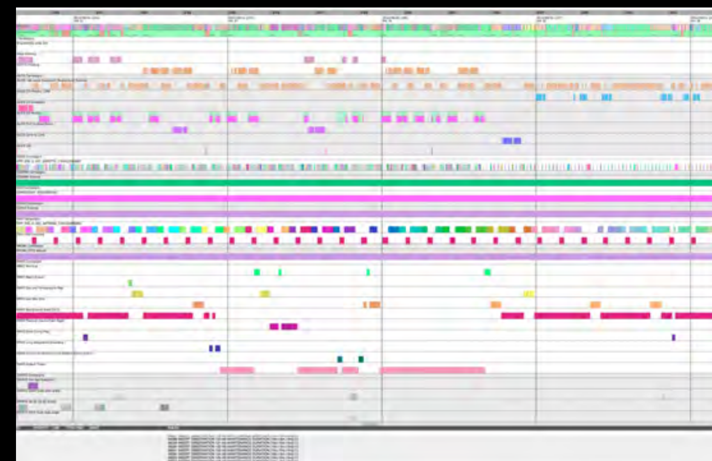
ESA's Rosetta Orbiter Operations (2014-2016)

Overview

- Ground Automated Science Planning used to develop over 30 Medium Term Plans (MTP) (~ 4 weeks each).
- Ground use of automated buffer scheduling from MTP through execution.

Details

- Critical to handling multiple contingencies around Philae Lander deployment, re-planning 4 weeks of operations within 24h due to Philae updates.
- MTP plans of up to 2000 activities, 2000 slews and pointings, 60 active science campaigns.

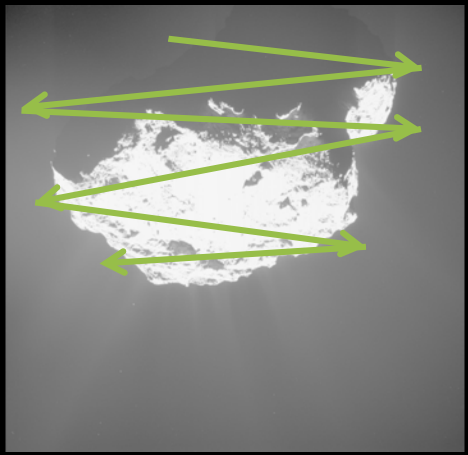


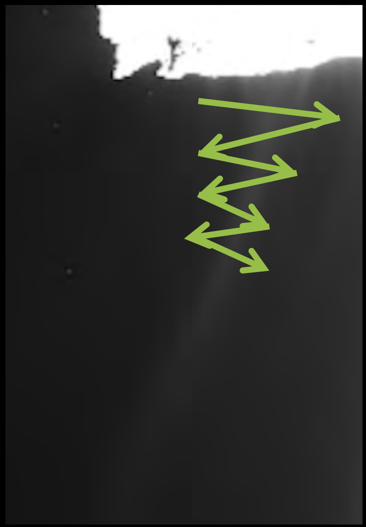
MTP 006 01 Aug – 01 Sep 2014: 32 days, 2027 observations, 2160 pointings and slews, 63 science campaigns, 10,000's constraints checked and over 1400 downlink dumps

See [Chien et al. 2021 JAIS] and [Rabideau et al. 2017 JAIS].

MTP 006 01 Aug – 01 Sep 2014: Zoom in on downlink plan for portion of MTP006

Broad Sweeps vs Targeted Sweeps



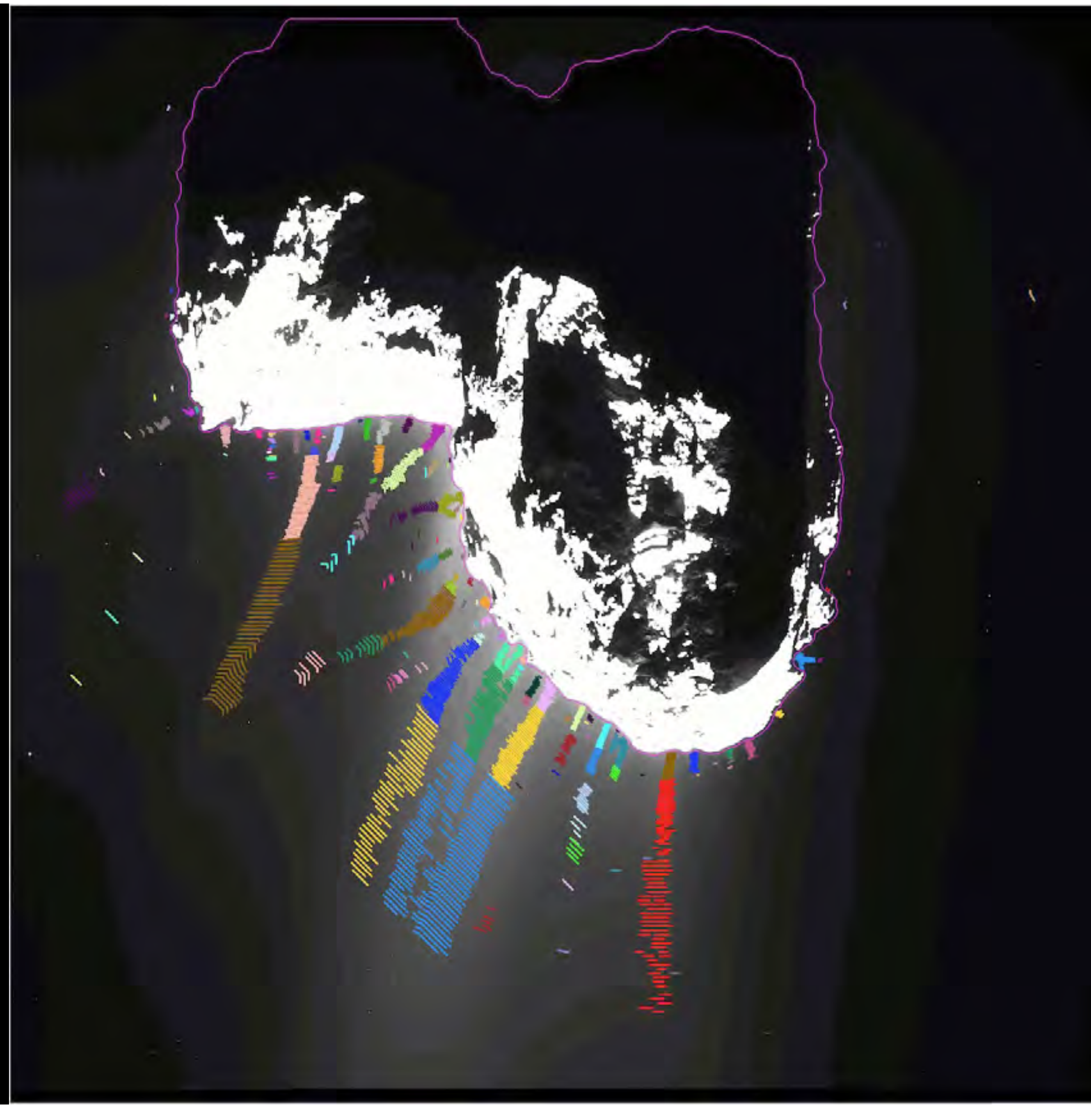


Plume Detection Rosetta OSIRIS

Brown et al. 2019 Astronomical J.

Collaboration w. H. Sierks/MPI

Original Image sequence credit: OSIRIS/MPI, Rosetta/ESA

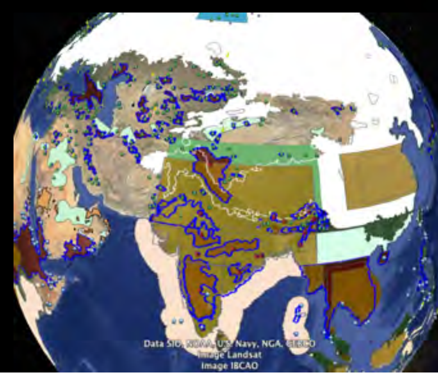


Coverage Scheduling

- Numerous missions involve variations of coverage scheduling, this technology is mature an in use for several NASA missions
  - ECOSTRESS: coverage, illumination, priority and background mapping, radiation keepouts, data management
  - OCO-3: visibility, illumination, complex geometry, area map prioritization, PMA calibration, complex rapid pointing and flip constraints
  - NISAR: data volume, power/energy, complex coverage campaigns

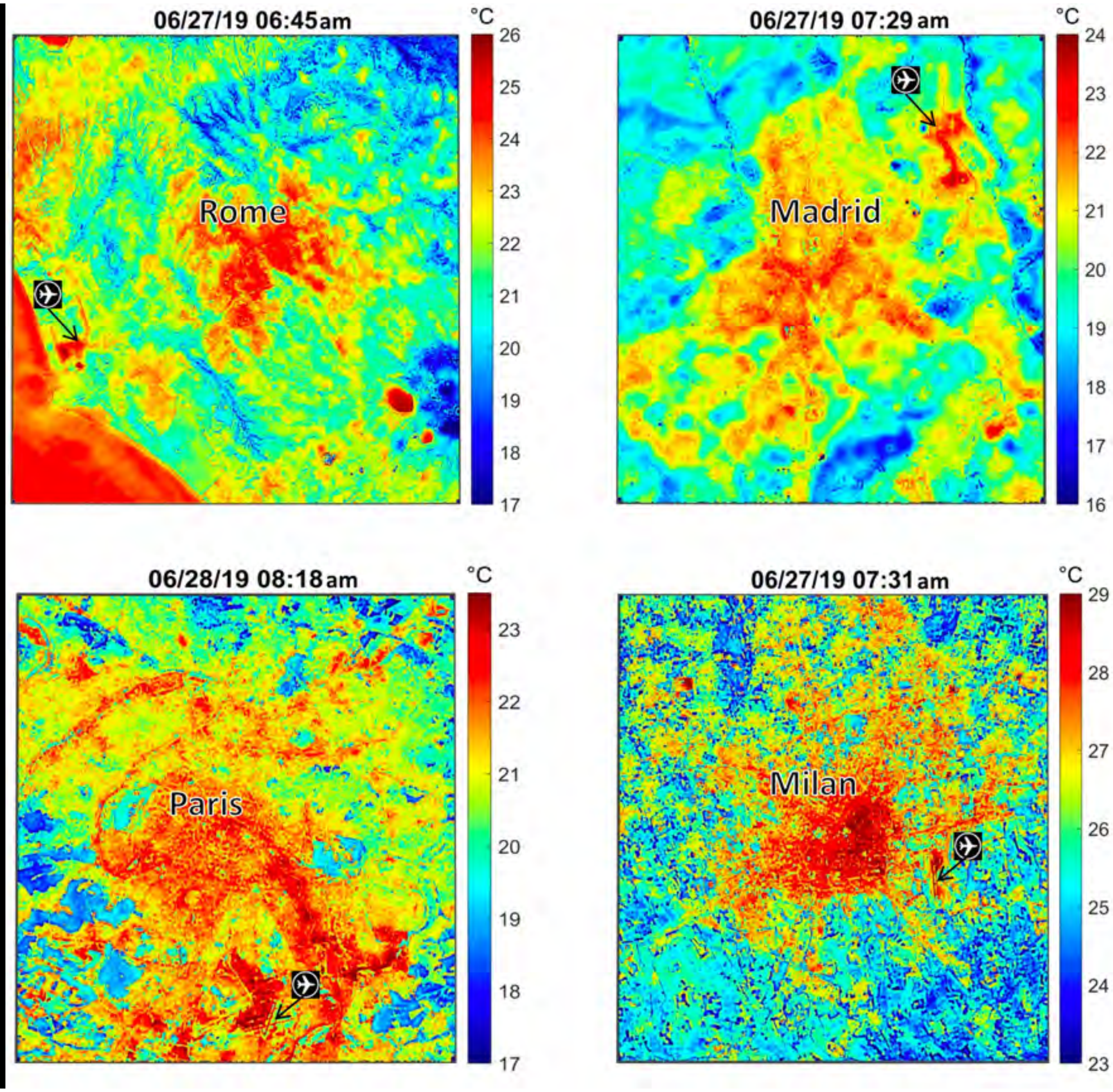
ECOSTRESS

OCO-3



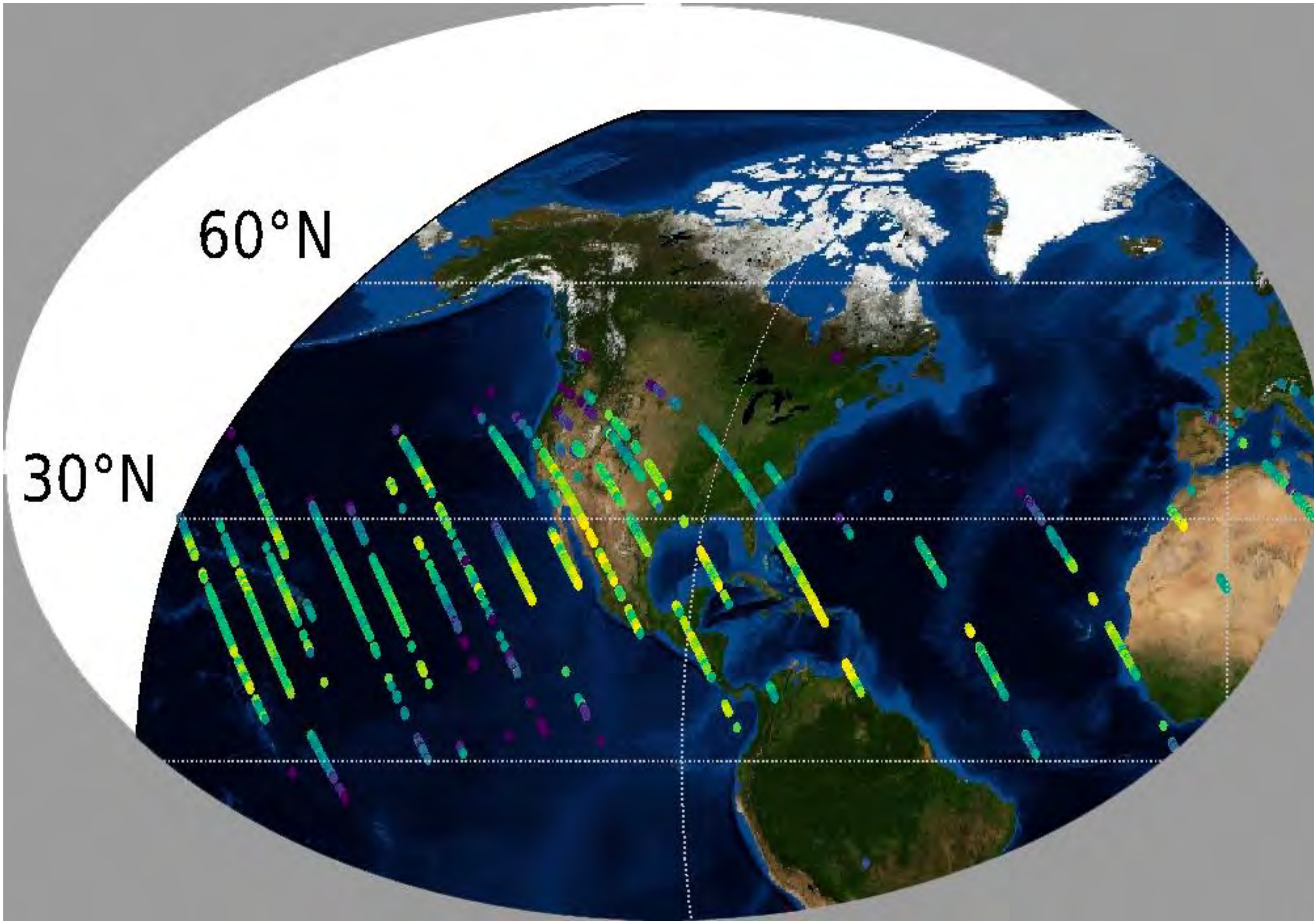
NISAR

POC: Chien, Wells, Doubleday



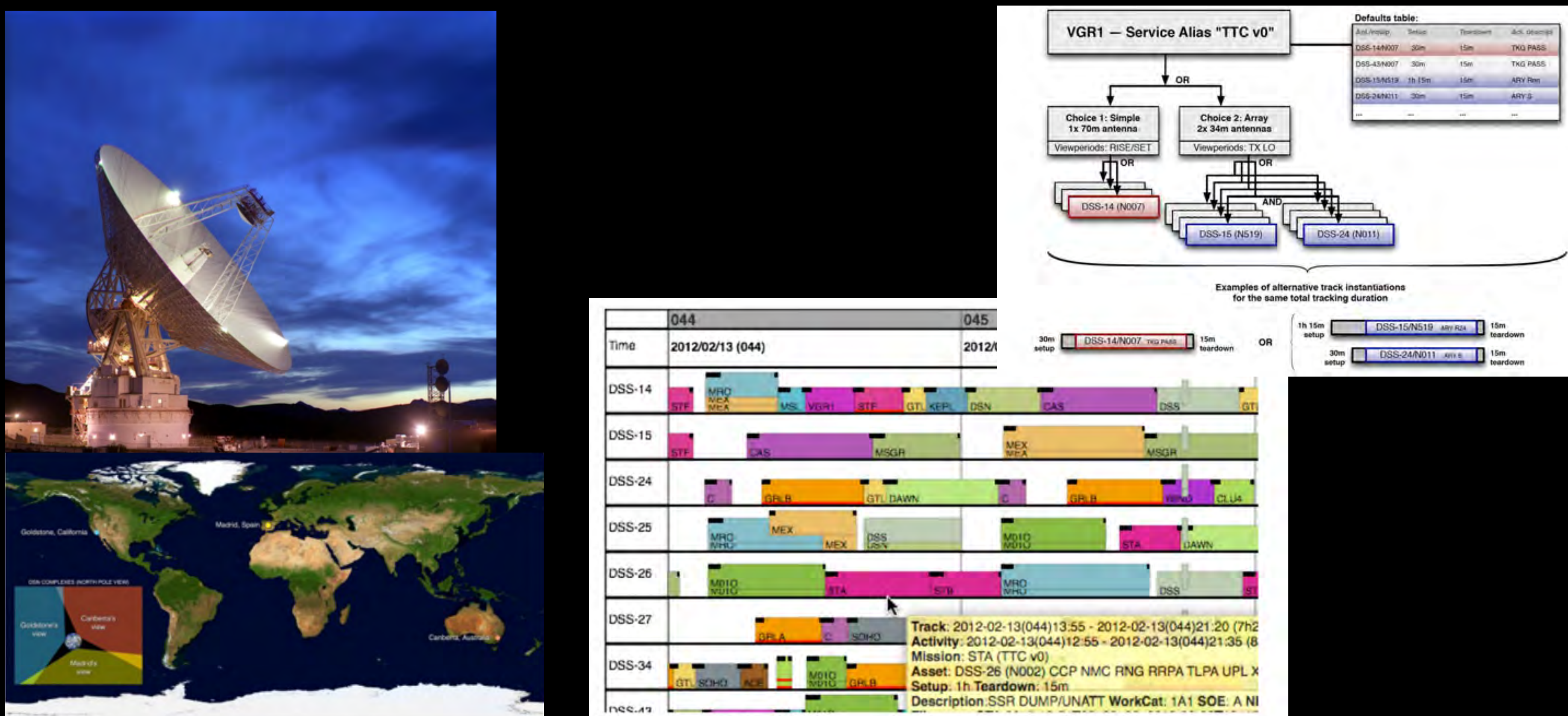
NEWS | JULY 2, 2019
NASA's ECOSTRESS Maps European Heat Wave From Space

https://www.jpl.nasa.gov/news/news.php?feature=7445



NEWS | JULY 12, 2019
NASA's Orbiting Carbon Observatory-3 Gets First Data

https://www.jpl.nasa.gov/news/news.php?feature=7452



Constraint based scheduling for NASA's Deep Space Network

Demand forecasting [SpaceOps 2018], Midrange scheduling [AIMAG 2014], near real-time scheduling

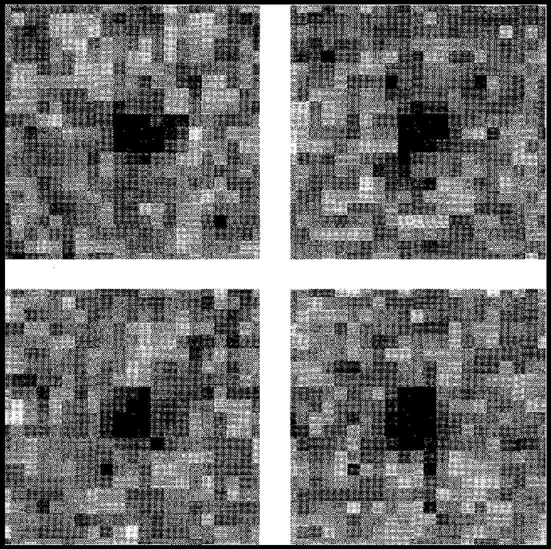
Link complexity based scheduling [SpaceOps 2018]

POC: M. Johnston

Machine Learning

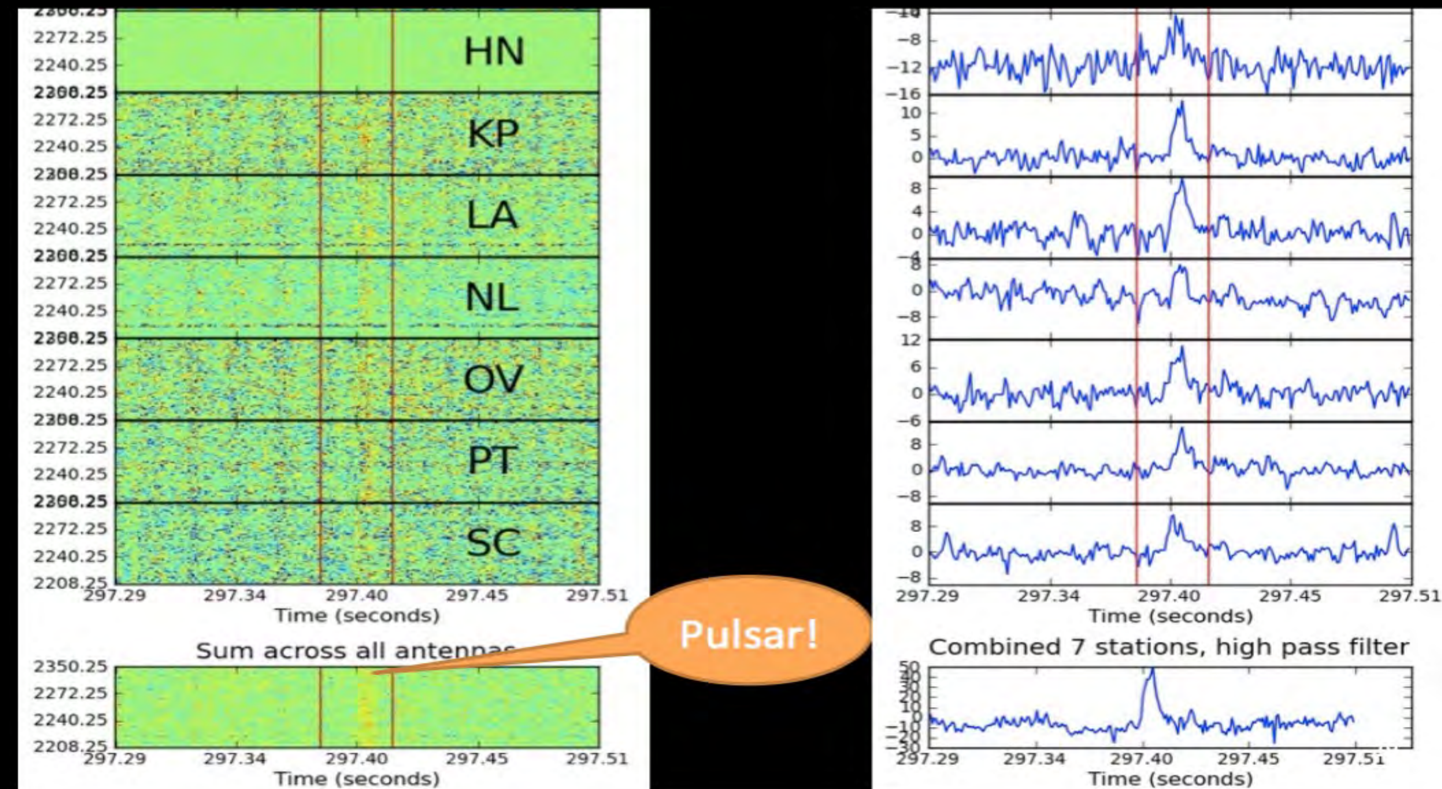
As far back as 1993 – Sky Image ClAssification Tool (SkICAT)

- Machine Learning (Decision Trees) used to classify 2nd Palomar Observatory Sky Survey
- Bootstrap from Digital to non digital data allows classification of more faint objects
- > 90% accuracy
- See Fayyad et al. 1993 ICML and Weir et al. 1995 Astronomical Society of the Pacific.
- But more recently…



Machine learning is used for optical astronomy to **triage <u>millions of optical events nightly</u>** for the Intermediate Palomar Transient Factory (i-PTF) [Waszczak et al. 2017, Masci et al. 2017] and the Zwicky Transient Facility (ZTF) [Mahabal et al. 2019, Masci et al. 2019].

Science (left) and reference (center) images used with Machine Learning to find true astronomical transient and variable objects (right).
POC: U. Rebbapragada/JPL



Machine Learning for Automated Triage/classification of Radio Transient Events
Very Long Baseline Array (VLBA)   Fast Transients Experiment (V-FASTR)
$10^5 \rightarrow 50$ per 24h
Random Decision Forests, continuous quality control and retraining.

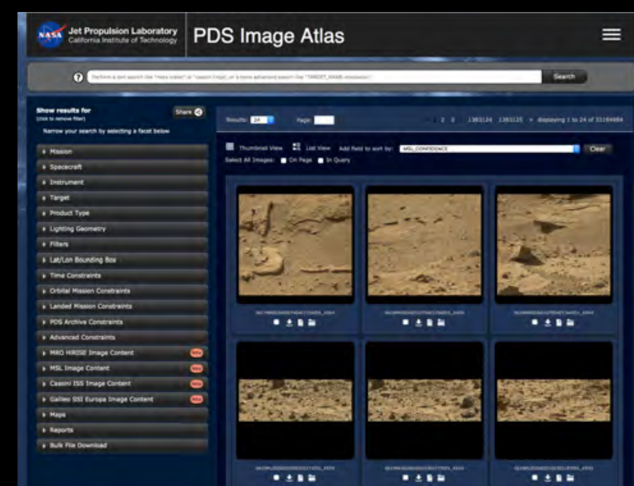
Wagstaff et al. Astronomical Society of the Pacific 2016

Deep Mars CNN Classification of Mars Imagery for the PDS Imaging Atlas

- MSL Rover data set[1]
  - 6,691 labeled images (Mastcam L/R eye, MAHLI)
  - 24 classes
- MRO HiRISE data set[2]
  - 10,433 labeled images
  - 8 classes
  - Augmentation: rotation, flipping, brightness adjustment

Figure 2. Example images for HiRISENet

Figure 1. Example images for MSLNet

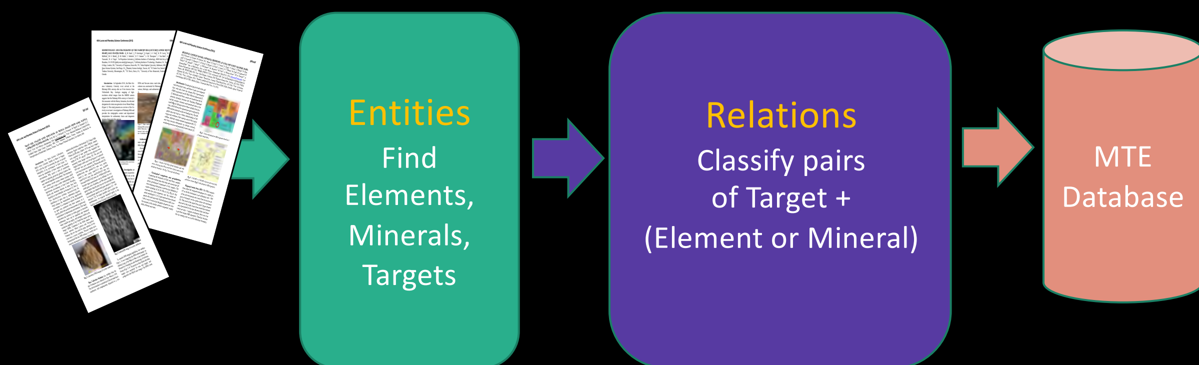


Result: Content indexing for PDS Atlas

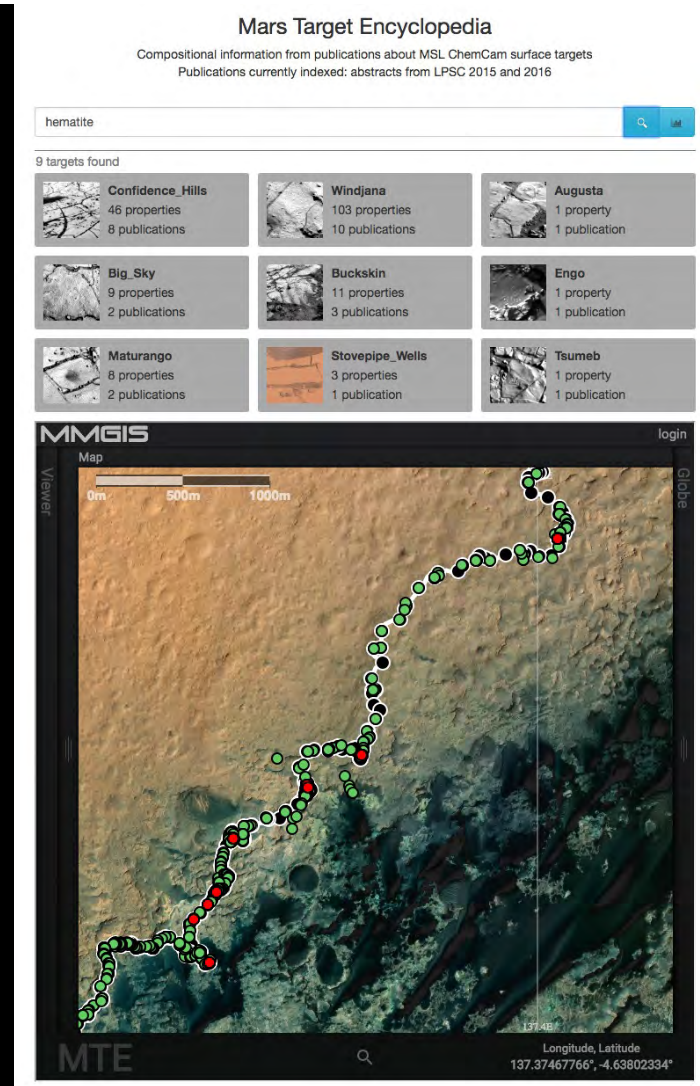
Wagstaff et al. 2018a IAAI

Mars Target Encyclopedia

- Lunar and Planetary Science Conference
  - Three years
  - 5,920 documents
  - 2-page abstracts
  - 7.2M words



Wagstaff et al. 2018 IAAI



Deep Learning for detection of fresh impact craters at Mars

See Daubar et al. JGR Planets 2022
Wagstaff et al. Icarus 2022.

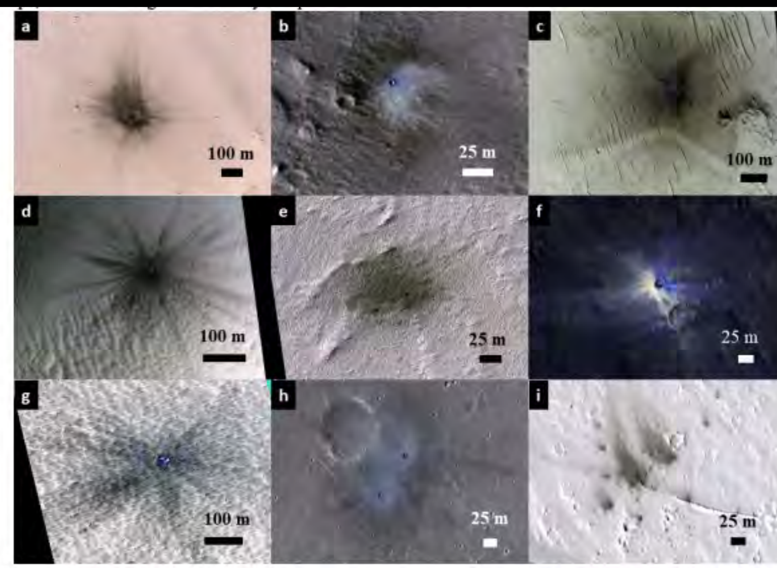


Figure 1. Albedo features around new dated impacts on Mars. Row 1: dual-toned single craters; (a) ESP_048888_1735: linear rays and a halo; (b) ESP_037544_2060: halo; (c) ESP_031965_2050: halo, linear, and arcuate rays. Row 2: single craters; (d) ESP_062128_1725: dark-toned linear rays; (e) ESP_017821_1820: dark-toned halo; (f) ESP_030566_1860: light-toned linear rays and a diffuse halo. Row 3: clusters of craters; (g) ESP_016954_2245: exposed ice and dark-toned linear rays; (h) ESP_053006_1980: dual-toned blast zone, halos, rays; (i) ESP_047175_1955: dark-toned blast zone, halos, rays. The left column have rays, the middle column have halos, and the right column have rays as well as halos. Images are from HiRISE enhanced-color RDRs, stretched for contrast, with North up. Image credit: NASA/JPL/U of A.

AI in Space:
The Future!

CADRE (2024 Launch)

- CADRE is a flight technology demonstration manifested as a payload on CP11 (CLPS)/ Intuitive Machines (IM-3) mission, targeting launch Apr 15th, 2024 on Falcon-9.
- 4 lunar rovers autonomously execute coordinated measurements
- Flight system uses Mexec onboard planner as “Strategic Planner” on leader with Mexec exec on each of 3 rovers

https://ai.jpl.nasa.gov/public/projects/cadre/

POC: JP de la Croix, PI, JPL
CL#22-6066

Europa Lander - Autonomy

On the Matanuska Glacier, AK July 2022

- Mission Concept Challenges:
  - Limited energy + radiation
    → limited lifetime
  - Large communication blackouts with Earth (> 42 out of every 85 hours).
  - Unprecedented level of model uncertainty.
- Autonomy required for Mission Success
  - Decision theoretic Approach Utility and Probability

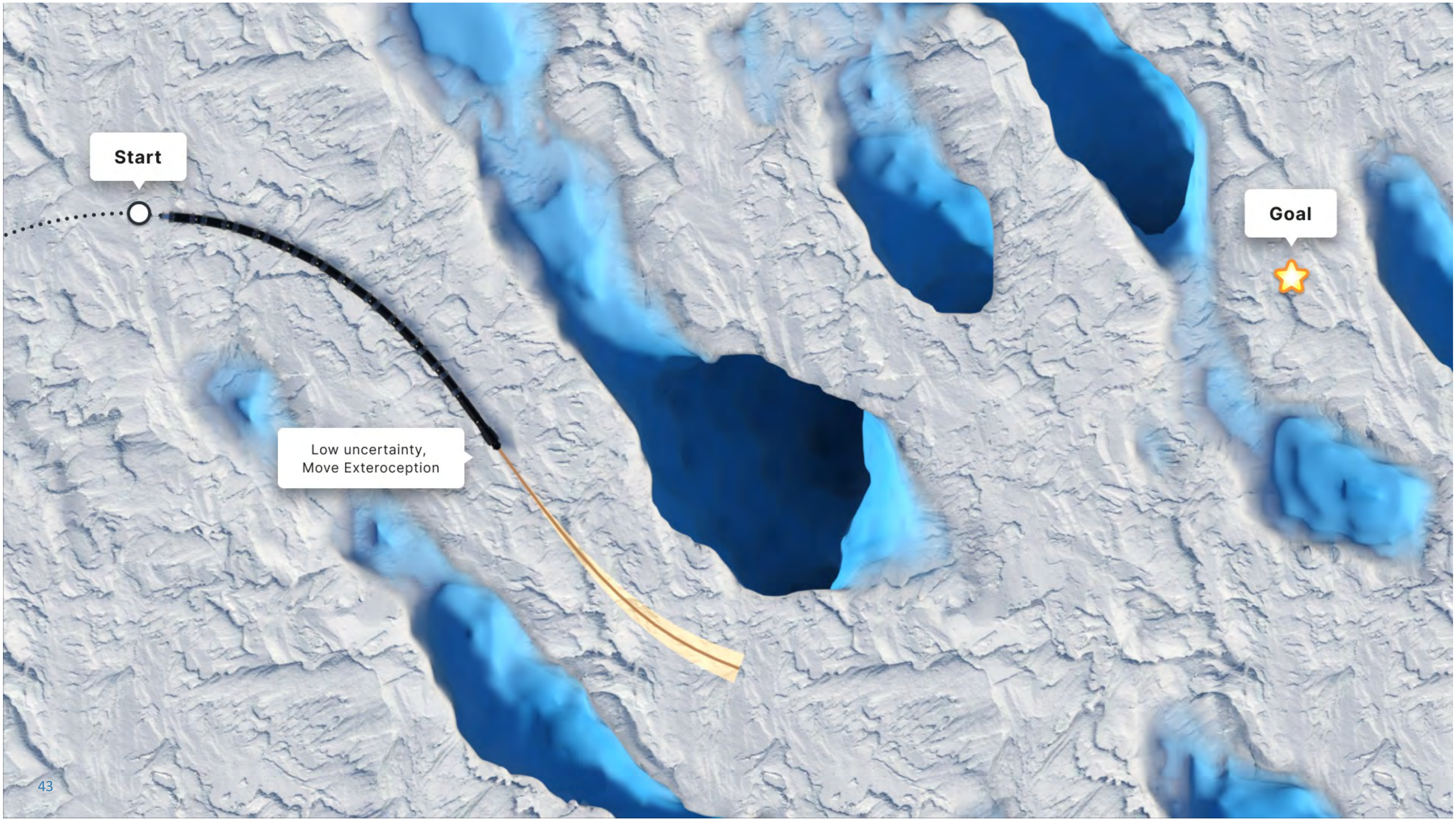
CL#22-5344

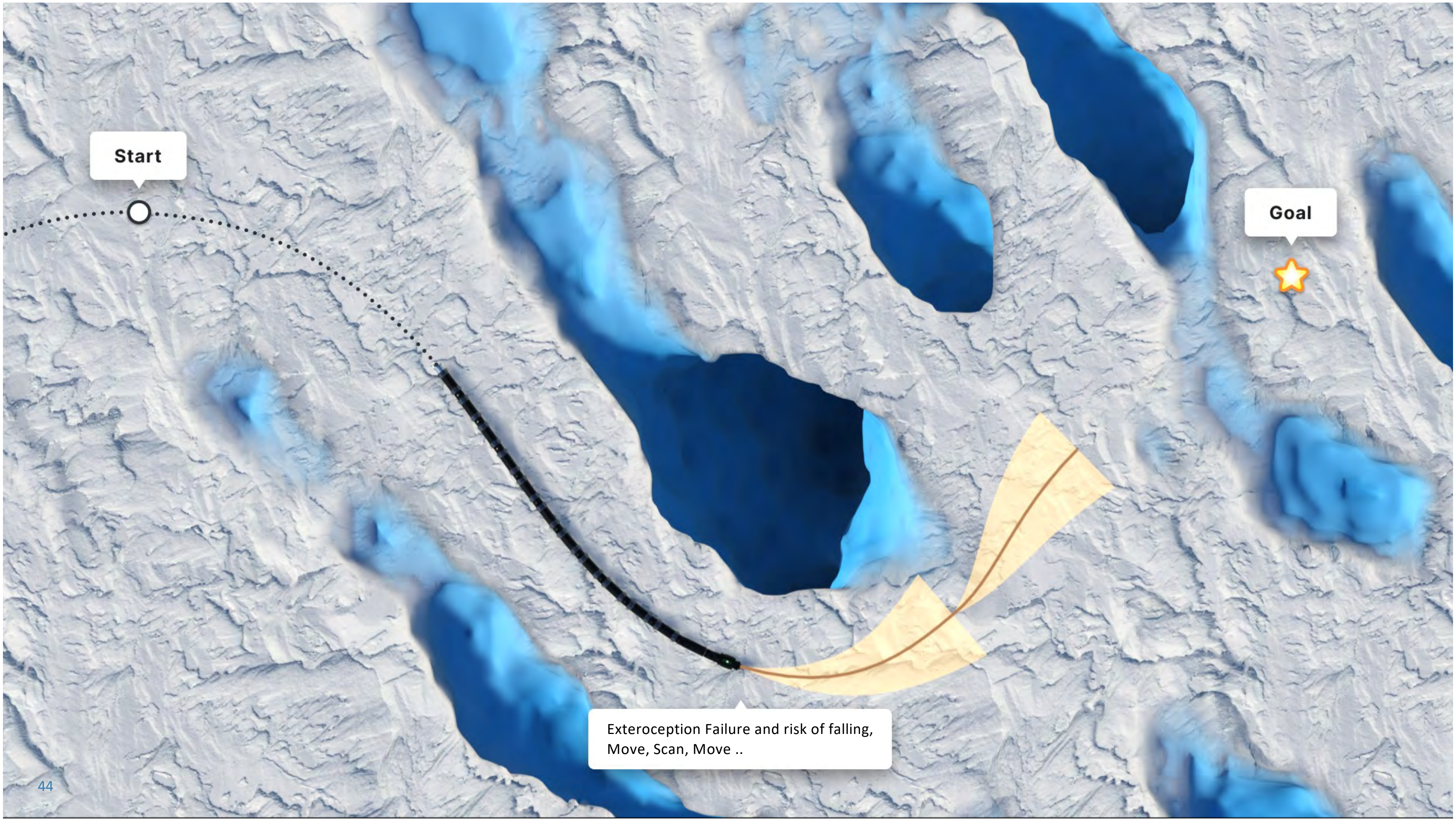
POC: S. Chien

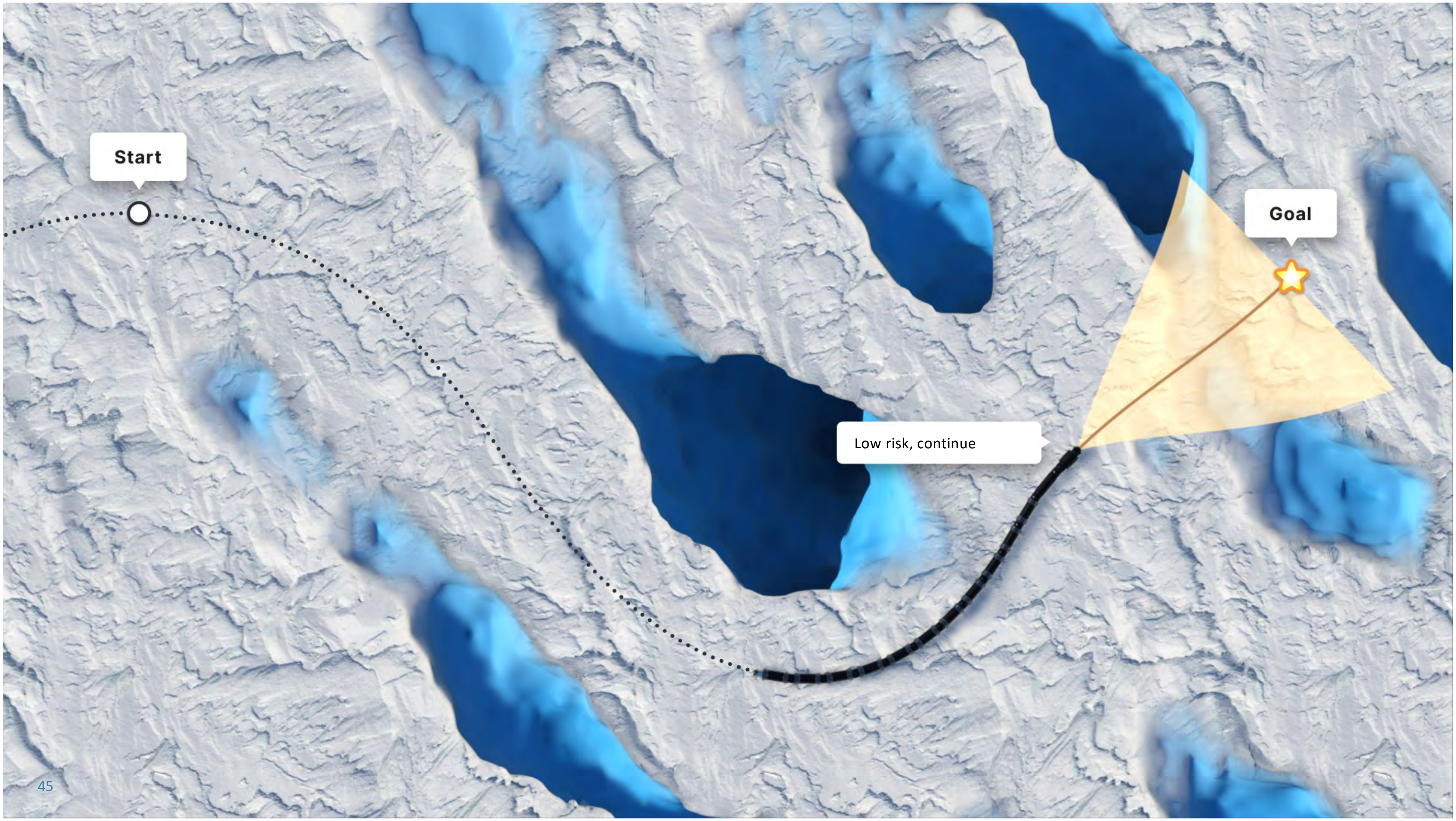
https://ai.jpl.nasa.gov/public/projects/europa-lander/

Exobiology Extant Life Surveyor (EELS) for Enceladus Exploration Mission Concept

H. Ono PI


Start
Goal
Low uncertainty,
Move Exteroception


Start
Goal
Exteroception Failure and risk of falling,
Move, Scan, Move ..


Start
Goal
Low risk, continue

EELS
Surface Mobility

- Screw-based gaits (e.g. leader-follower)
- Shape-based gaits
- Hybrid gaits

NewScientist

Steve Chien interview: Why NASA is inventing curious AI for deep space

Space probes will be the first to explore the furthest reaches of our solar system and beyond. To make discoveries like finding alien life, they will need to think more like humans, says NASA's Steve Chien

SPACE 20 October 2021

By Neil Briscoe

Why we need curiosity?

Curiosity is a quality related to inquisitive thinking such as exploration, investigation, and learning -- Wikipedia

Filling in the blanks versus investigation of the ***true unknown***.

Lewis and Clark 1804-1806

Pacific Ocean

Modern Day St. Louis, MO

8000 miles   Over 2 years

Products

- 2 years

- Maps, 120 animal specimens, catalogued 200 plants

- → 18 4x6” notebooks
- ~ 750 pages

- In contrast modern space mission brings down gigabytes per day
  1 GB = 678,000 pages of text *per day*

Lewis and Clark 1804-1806

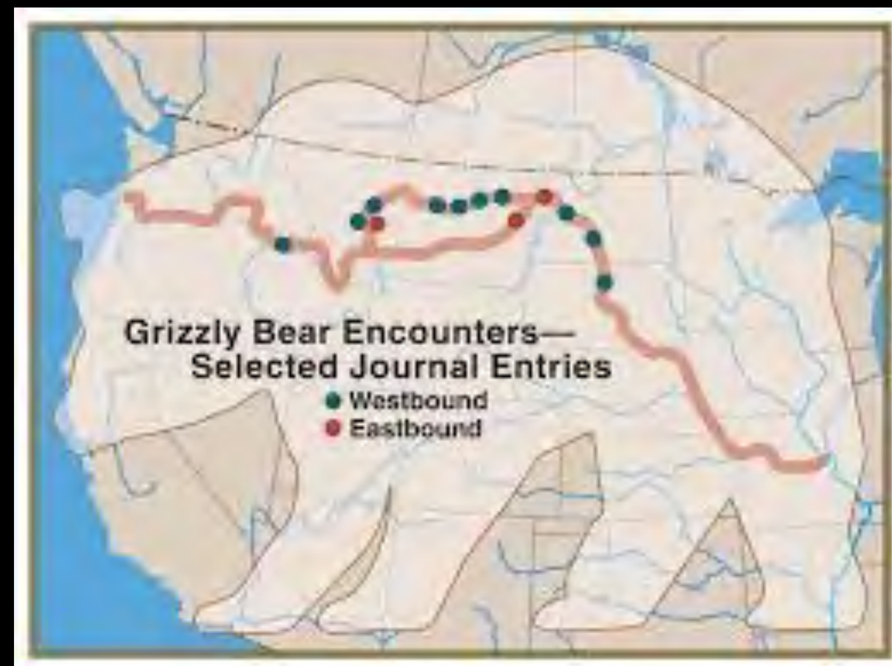
wildlife

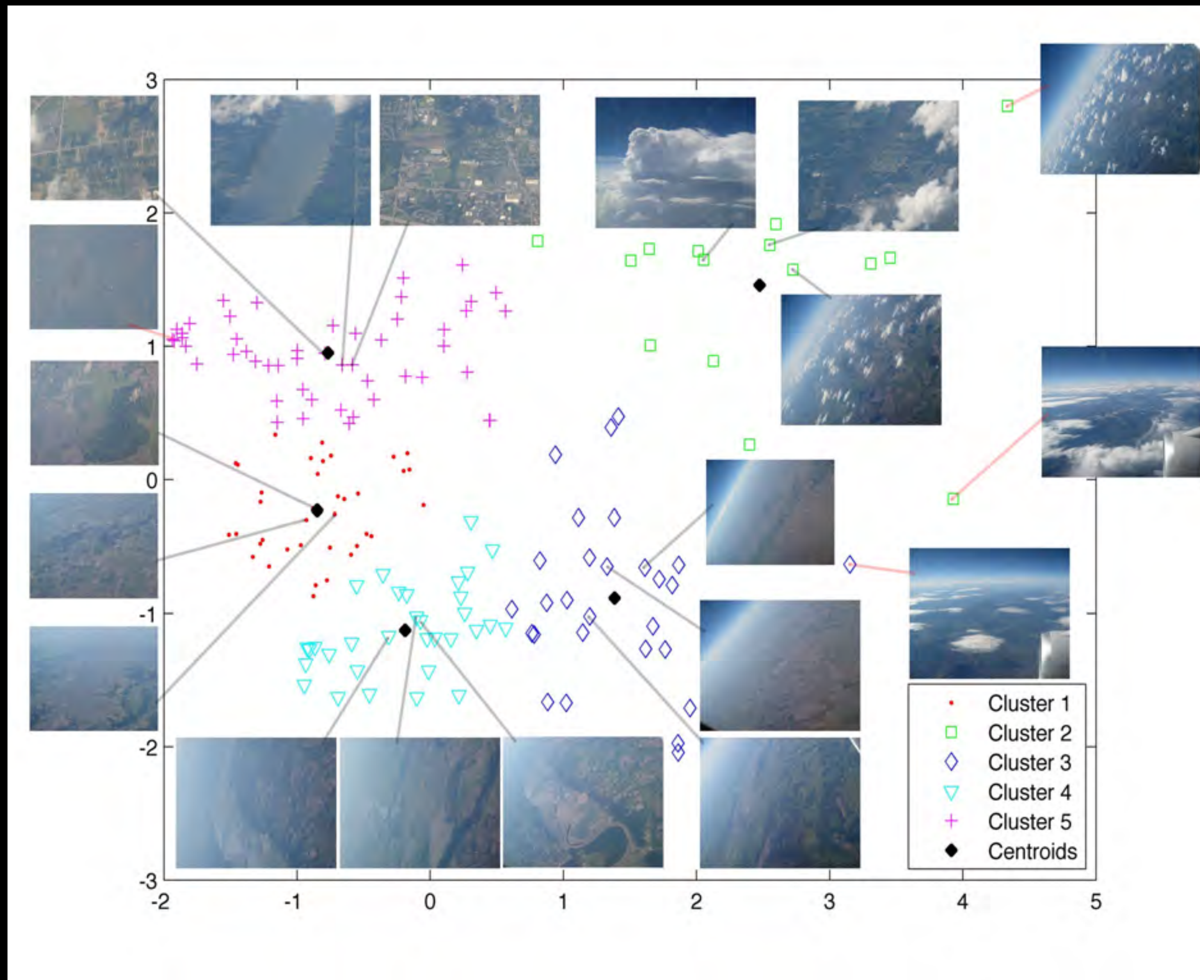
mountains

rivers

lake


Bison Along the Trail —
Selected Journal Entries
Westbound
Eastbound


Grizzly Bear Encounters—
Selected Journal Entries
Westbound
Eastbound



Clustering and Metric Learning of Aerial Imagery [Hayden et al. 2012 ACM TIST]

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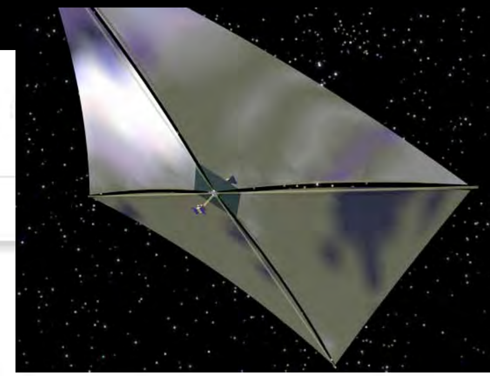


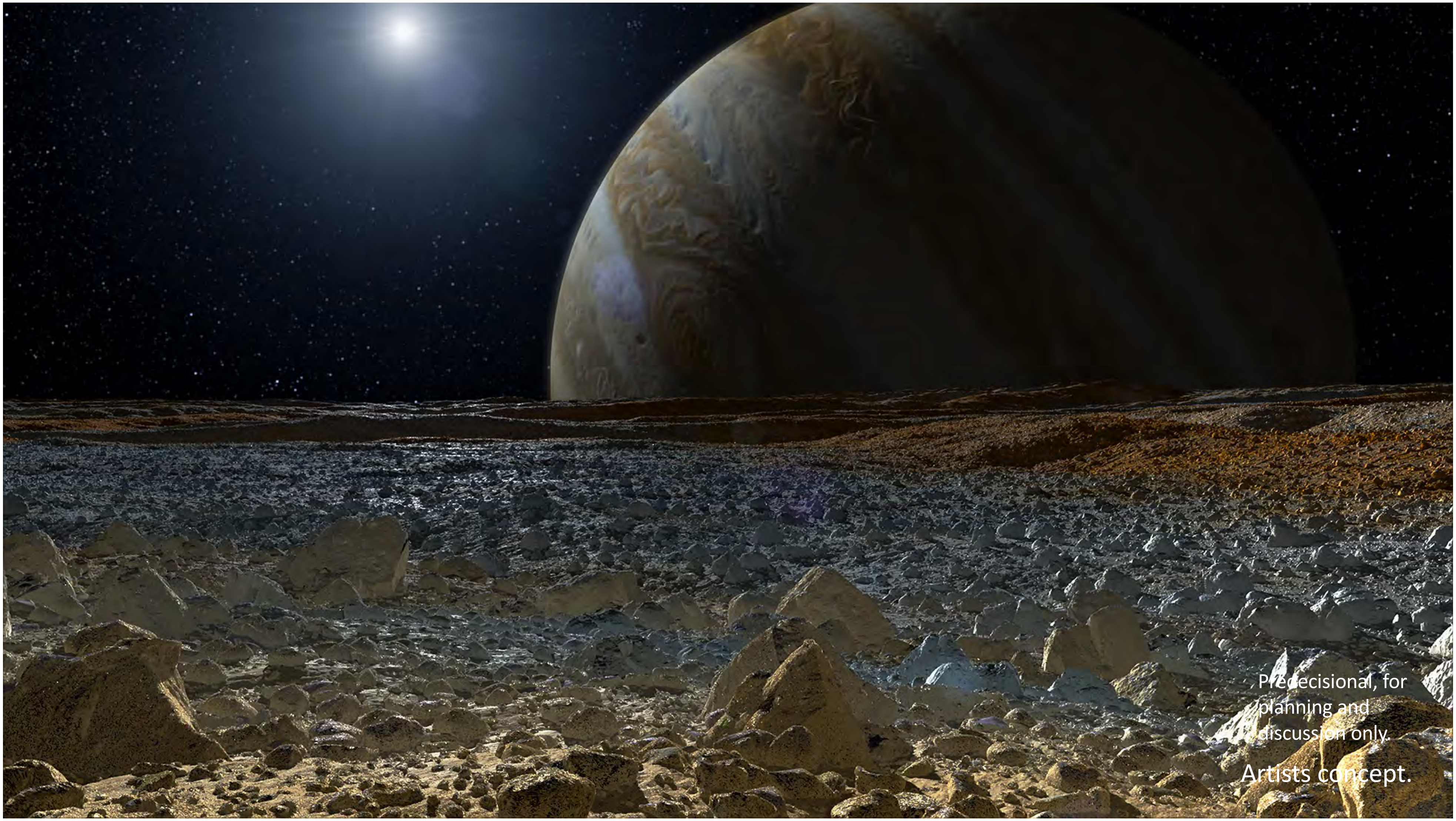
LATEST

ENGINEERING

How NASA's Search for ET Relies on Advanced AI

Jet Propulsion Laboratory's artificial intelligence chief describes the "ultimate" test for AI in space exploration

By Larry Greenemeier on December 28, 2017


Predecisional, for planning and discussion only.
Artists concept.

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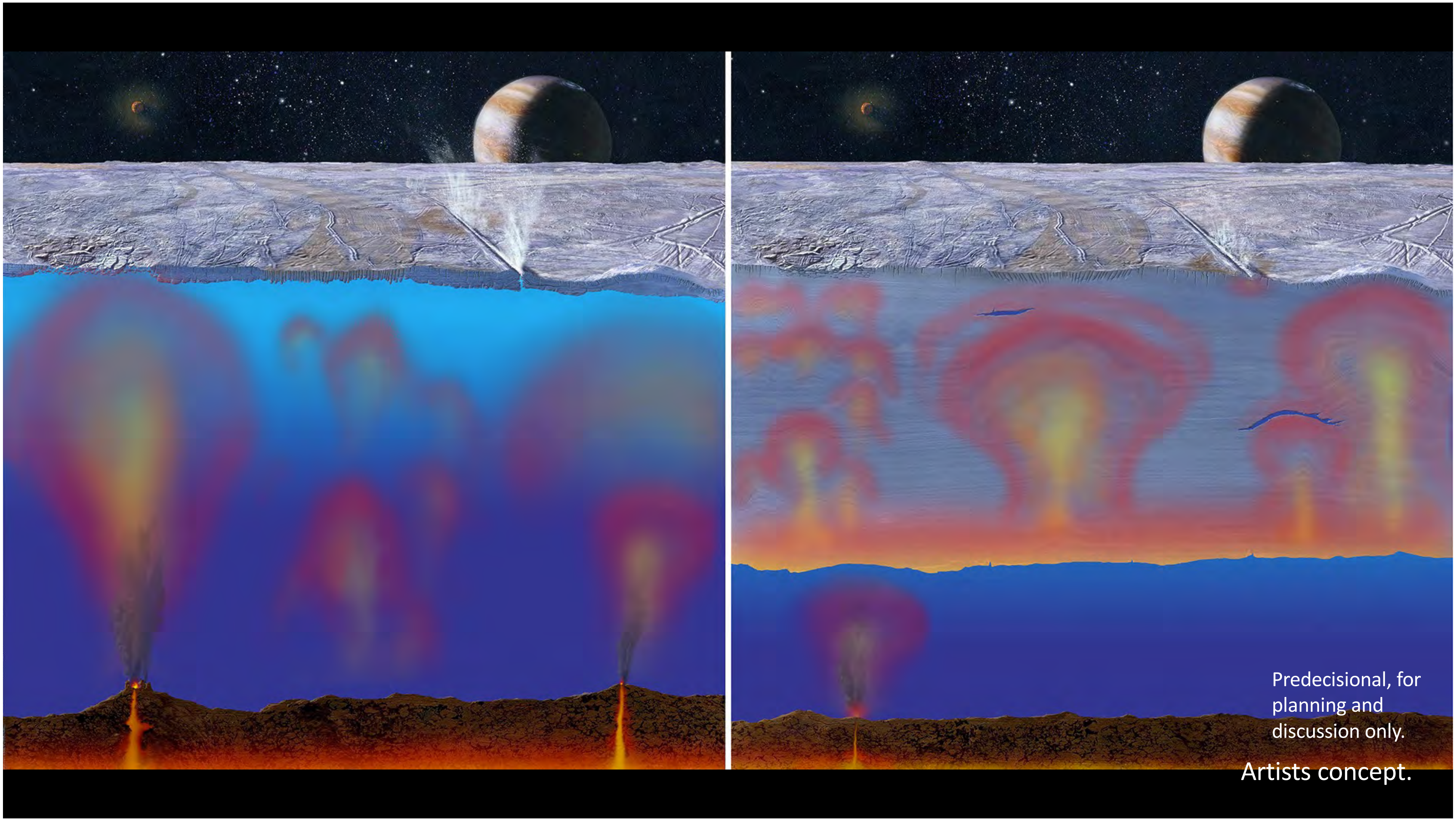
Artists concept.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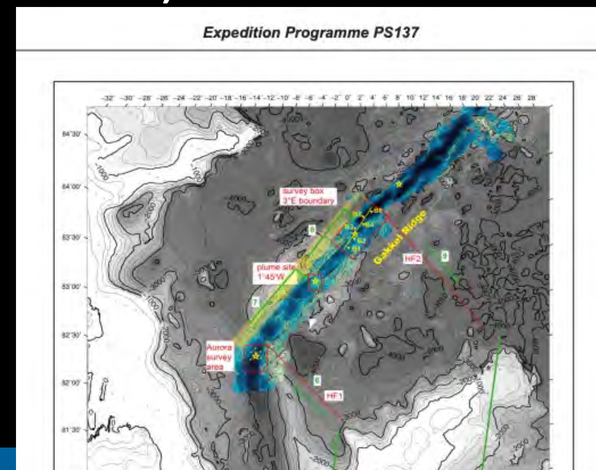
Ocean Worlds submersible concept.

From the Polarstern Cruise PS137 (Alois)

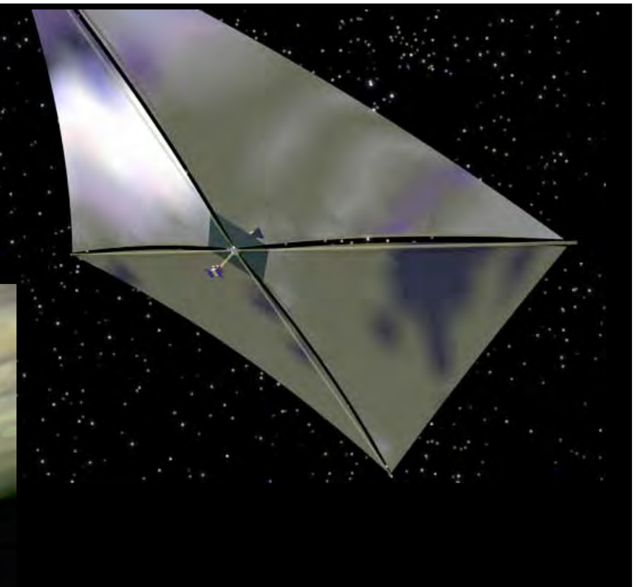
Gakkel Ridge

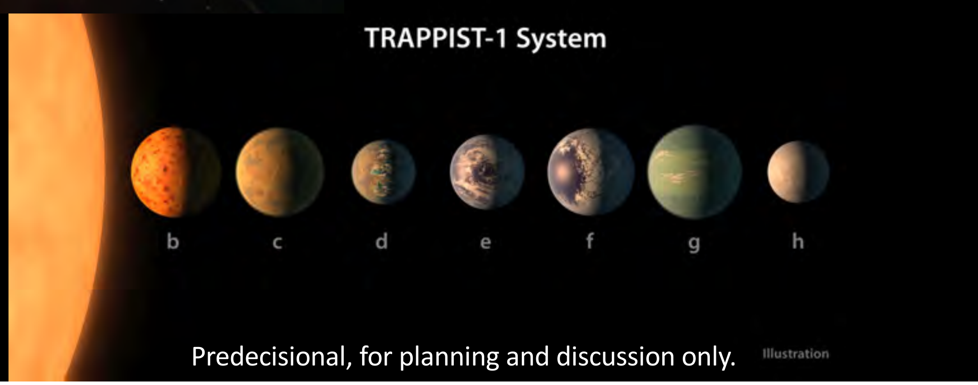
Courtesy PS137 NUI team. © Copyright WHOI.

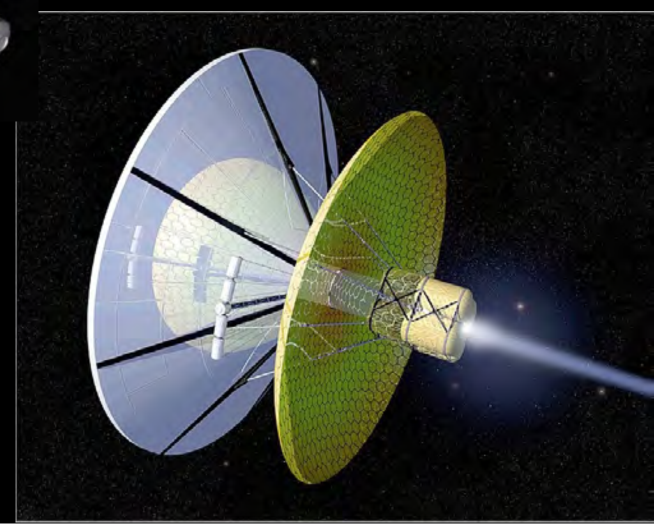


26 June – 1 August 2023

Interstellar Mission Concepts







Artists concepts.

Predecisional, for planning and discussion only.

DARE MIGHTY THINGS

Jet Propulsion Laboratory
California Institute of Technology