Dare Mighty Things Together

Designing Human-Machine Teaming in Robotic Space Missions

So Young Kim, Ph.D.
Chief Engineer
JPL Point of Contact for HSI

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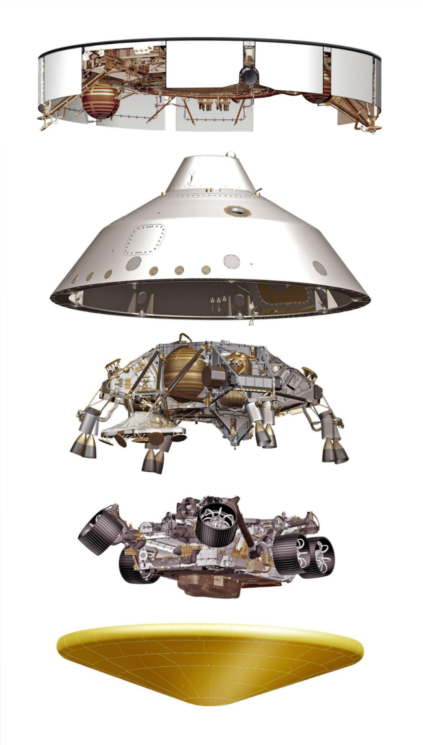
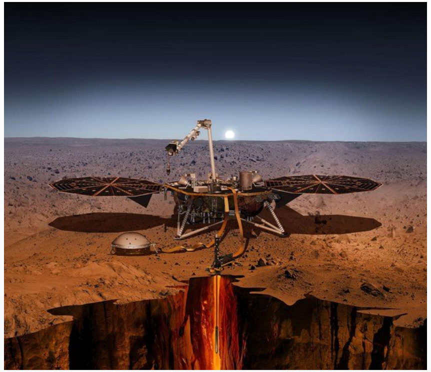
Jet Propulsion Laboratory
California Institute of Technology

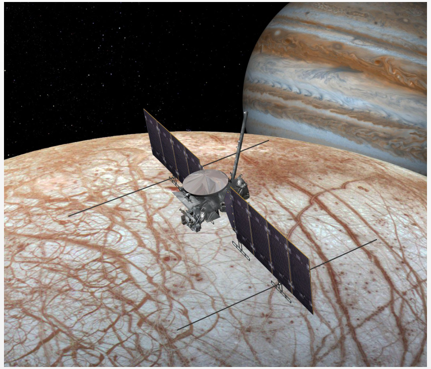
HSI

The goal of HSI is to “**optimize total system performance** (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability.” (DoD 2003.)

Deep Space Robotics Missions at JPL







Clockwise order: Five major components of the Mars 2020 spacecraft, Psyche Spacecraft, InSight Lander on Mars, Cassini versus Saturn, Europa Clipper spacecraft (All are artist's concepts.)

There is no human in robotics missions so no HSI is needed, right? …

COMMON MISCONCEPTION OF HSI

Juno Approaches Jupiter (Artist's Concept)

What about them?



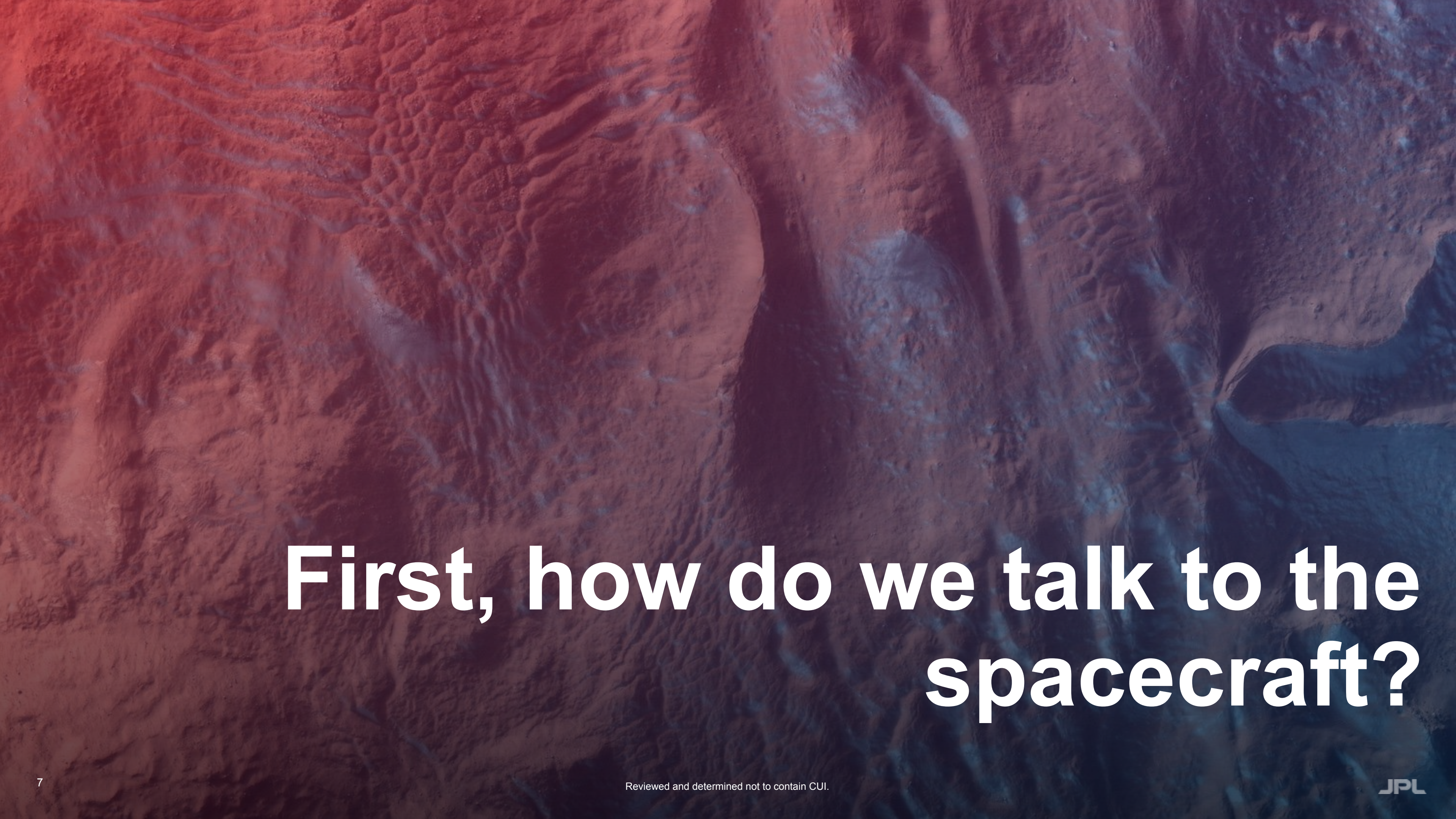


Left to Right order: Psyche Assembly Launch Testing Operation (ATLO), Operations team on the landing day for Perseverance, Pitstop at JPL (Perseverance), InSight Logistics, Folks riding on Juno (the Roman god Jupiter, his wife Juno and Galileo Galilei), Mars 2020 Operations team during the planned course correction maneuver

How do ground operations team interact with spacecraft in flight?

HUMAN-MACHINE TEAMING FOR JPL'S MISSIONS

The Mars 2020 navigation team celebrates Perseverance's nominal, or successful, trajectory correction maneuver in the Mission Support Area at NASA's Jet Propulsion Laboratory



First, how do we talk to the spacecraft?

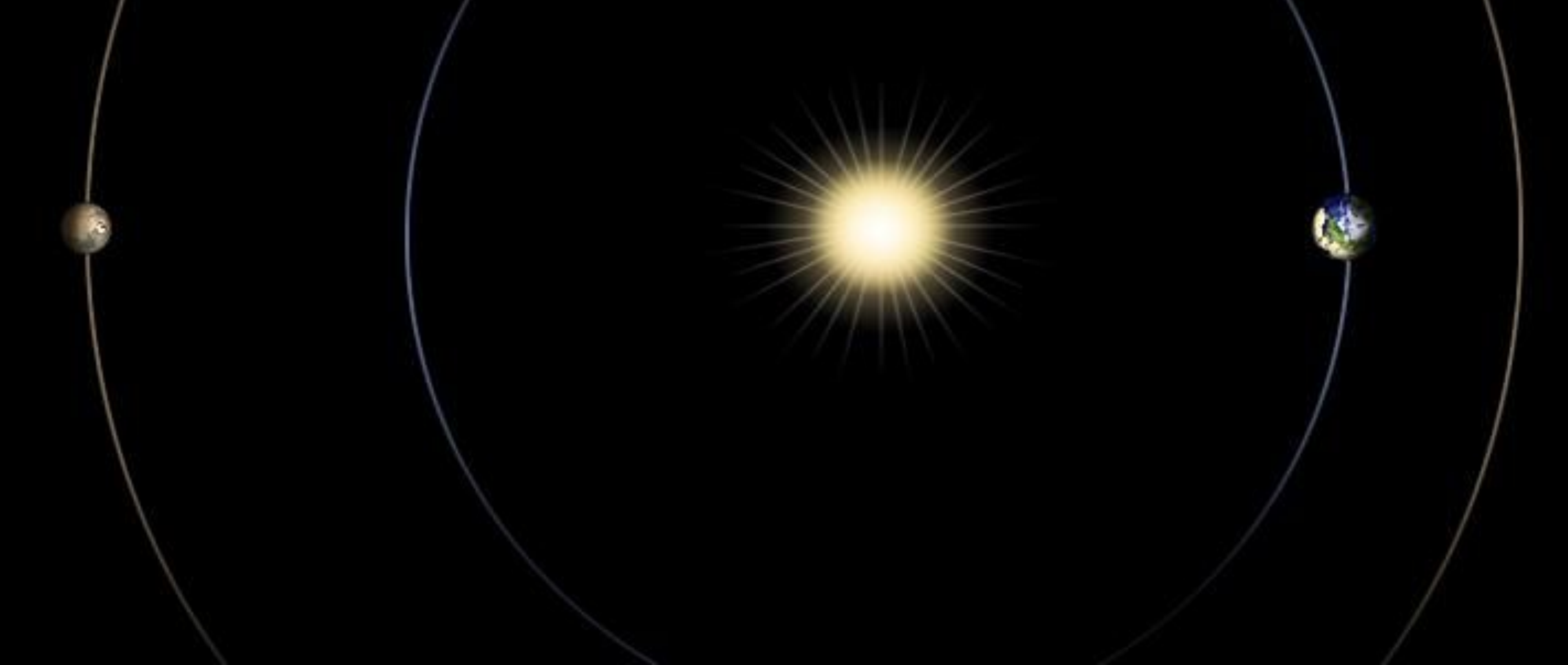
Deep Space Network is our window to the deep space exploration

Madrid Deep Space Communication Complex – part of NASA's Deep Space Network

In a historic first, all six radio frequency antennas at the Madrid Deep Space Communication Complex – part of NASA's Deep Space Network (DSN) – carried out a test to receive data from Voyager 1 spacecraft at the same time on April 20, 2024.
Credit: MDSCC/INTA, Francisco "Paco" Moreno

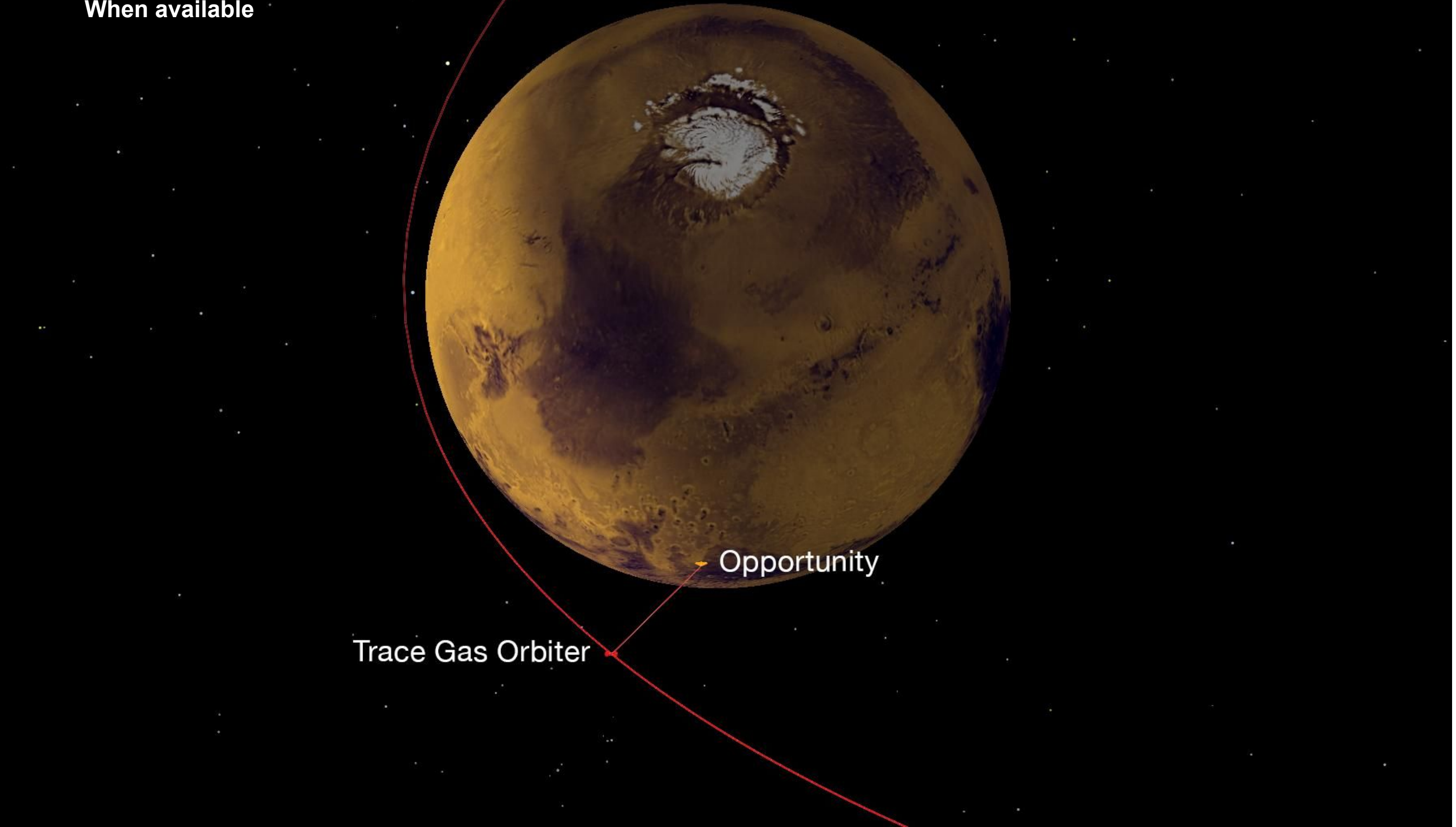
Geometry matters a lot

Communication challenges in context - in the case of Solar Conjuction on Mars



So We do Relay Communication via orbiters

When available



Strengthening the Mars Telecommunications Network

A NASA radio aboard ESA's Trace Gas Orbiter, succeeded in its first test of receiving data transmitted from NASA Mars rovers. This graphic depicts the geometry of Opportunity transmitting data to the orbiter, using the UHF band of radio wavelengths. Credit: NASA/JPL-Caltech/ESA

Glimpse into Mars surface ground team’s life (and the rover’s)

Working hard | Sleeping | Working hard

One Way Light Time
4 to 20 mins

Data Rate
500 bps upto 32 kbps via Direct-To-Earth
(or 2 Mbps via an relay asset)

Downlink

Downlink Assessment

Planning and Commanding

Uplink

Biggest headaches for the ground team

You have only "texting" as a means of communication with your child. And it takes about 20 mins to send a text and 7mins to receive a text. And your child is in some remote location so the connection is spotty and inconsistent.

Intermittent communications

You can only communicate when the rover is in "communicative" configuration. And you can only communicate when the rover is line of sight from Earth (for DTE) or an relay asset (e.g., orbiters like MRO, TGO, etc.)

Delayed communications

It takes about 4 to 20 minutes for a data to be transmitted. So knowing whether your communications have been successful takes about 14 minutes. Because of this and many other reasons, the ground team preplans for a day of activities for the rover, and send them at once. You only get the results of it at the end of the rover's day.

Limited data bandwidth

Data bandwidth with Mars operations varies from 500 bps to 2Mbps depending on the availability of an relay assets and performance of the communications link.

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Limited Visibility and Real-Time Commandabilty into the Spacecraft

You can only communicate when the rover is in "communicative" configuration. And you can only communicate when the rover is line of sight from Earth (for DTE) or an relay asset (e.g., orbiters like MRO, TGO, etc.)

It takes about 7 minutes for a data to be transmitted. So knowing whether your communications have been successful takes about 14 minutes. Because of this and many other reasons, the ground team preplans for a day of activities for the rover, and send them at once. You only get the results of it at the end of the rover's day.

Data bandwidth with Mars operations varies from 500 bps to 2Mbps depending on the availability of an relay assets and performance of the communications link.

How are we operating these missions, then?

- Currently most space missions (especially Flagship - the largest class of Planetary Exploration missions) are operated by the operations team providing the full list of activities to do until the next time they can communicate with the spacecraft.
- In typical Mars surface operations, it is basically a list of 1 to 3 Sols worth of things to do. (1 Sol corresponds to 1 Martian day).
- The spacecraft has barely any freedom to veer off from that unless there is a fault, at which time the predefined fault management capabilities kick in.
- The basis of operation paradigm is currently “do exactly what I say. If you can’t, call me and wait until I can tell you what to do.”

Ingenuity's Team Waits for Data on Helicopter's First Flight

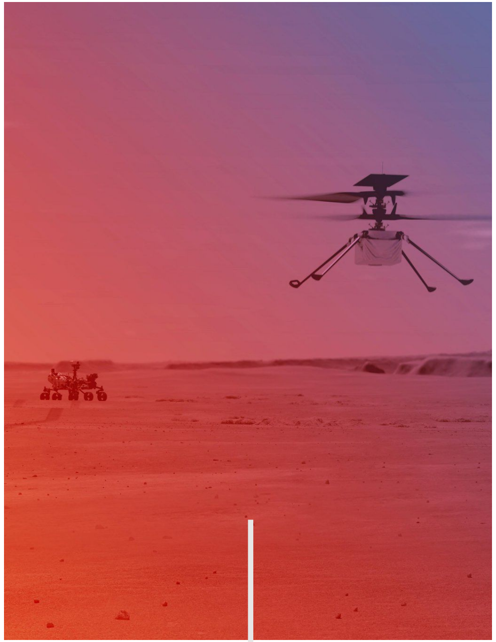
What Happened

Members of NASA's Ingenuity helicopter team in the Space Flight Operations Facility at NASA's Jet Propulsion Laboratory react to data showing that the helicopter completed its first flight on April 19, 2021.

Credit: NASA/JPL-Caltech

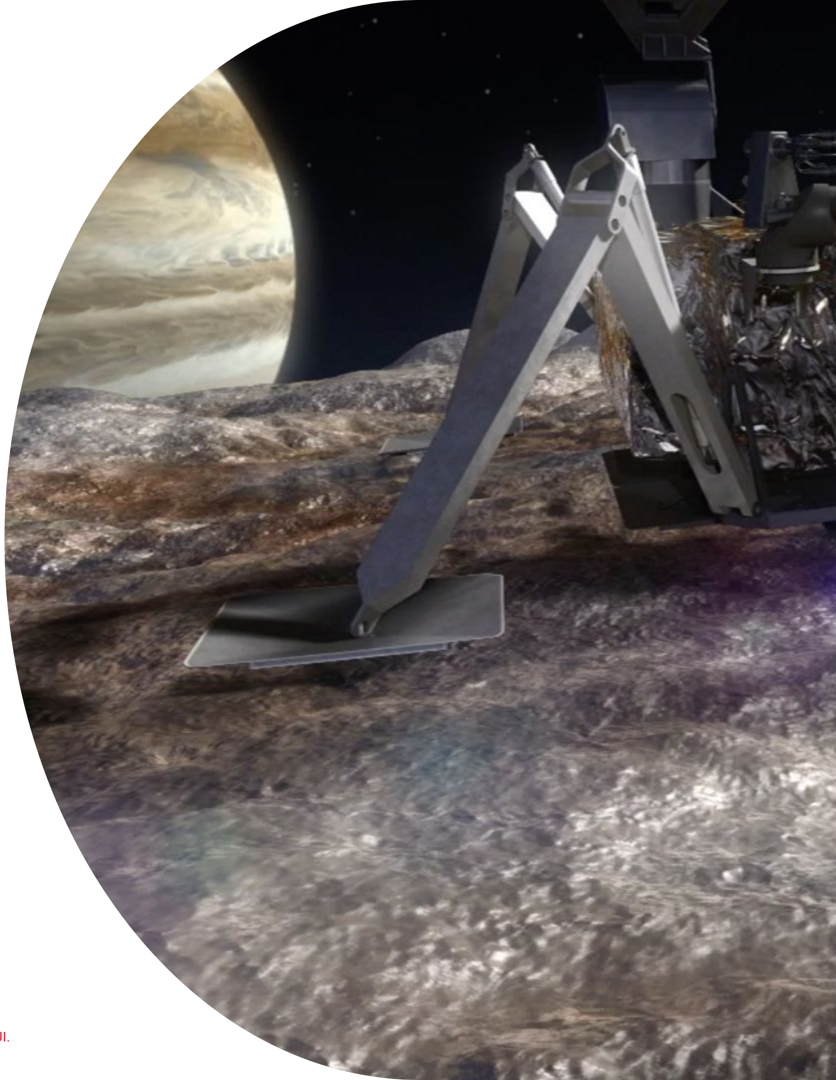
What are the key challenges in Human Machine Teaming in your domains?

Break out into groups
Silent brainstorming (2 mins)
Discuss within the group (5 mins)
Share



What about interacting with highly autonomous spacecraft?

Wouldn’t we need a new operational paradigm to interact with highly autonomous spacecraft?



Europa Lander

Concept Study

1. Search for evidence of **biosignatures** on Europa.

1. Assess the **habitability** of Europa via *in situ* techniques.

1. Characterize the surface and subsurface.

Context of operating Europa Lander mission

~48hrs Comm Blackout (Length of Europan Night) followed by ~32 hrs of Comm Feasible Duration (Length of Europan Day)

48 kbps Data Rate for Direct To Earth (no relay satellites)

~50 mins One Way Light Time

Definite End of Mission ~30 earth days

Even more extreme than Mars

Mars missions

7 minutes OWLT

2 Mbps data rate

Daily communication

Time is the ground team's best friend.

Europa Lander

45 minutes OWLT

48 kbps data rate

48 hours of communication blackout

Time is the most precious resource.

Even more extreme than Mars

Mars missions

7 minutes OWLT

2 Mbps data rate

Daily communication

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Europa Lander

45 minutes OWLT

48 kbps data rate

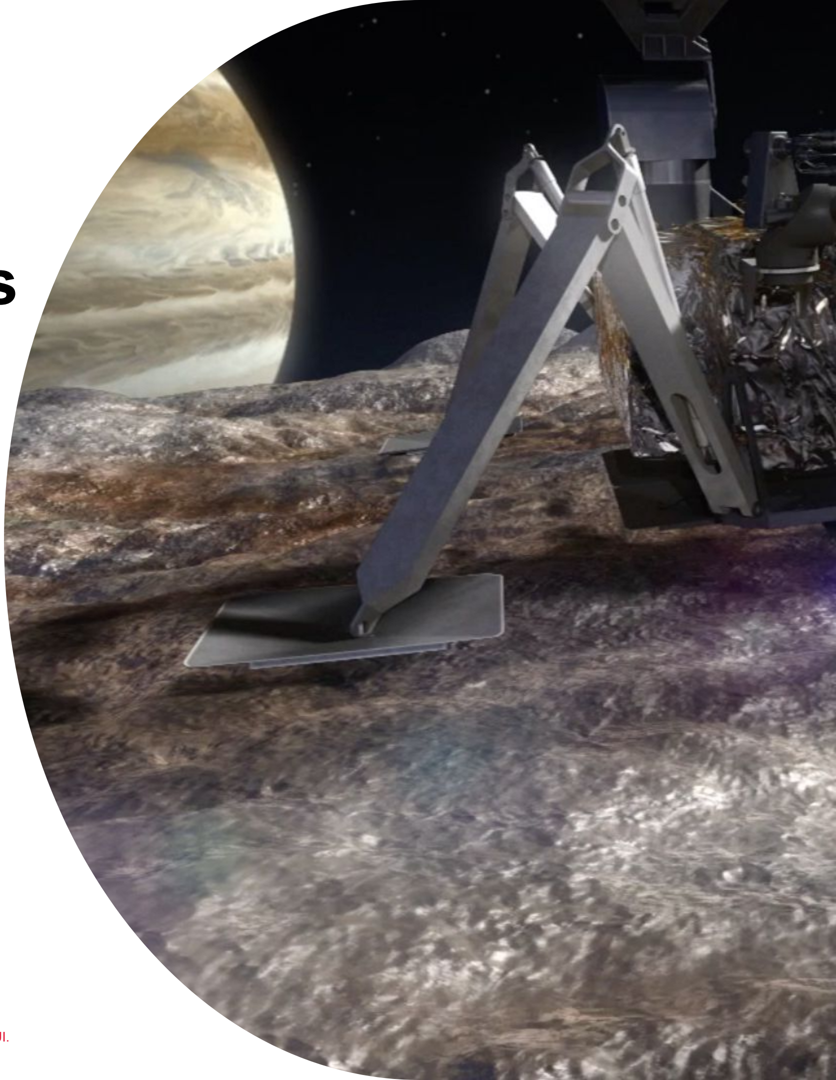
48 hours of communication blackout

Time is the most precious resource.

Need for higher level of autonomy

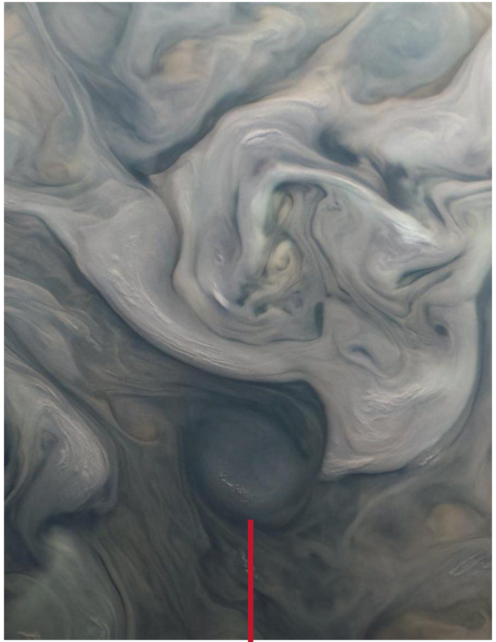
How can we best optimize our mission by balancing capabilities of humans and autonomy?

HSI approach to Human-Machine Teaming



How would you go about it? What questions do you have? What do you need to learn first?

Break out into groups
Silent brainstorming (2 mins)
Discuss within the group (5 mins)
Share



Swirling clouds on Jupiter are shown in an image taken by the JunoCam public engagement camera aboard NASA's Juno spacecraft on Feb. 25, 2022.

Biggest headaches for the ground team

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PLUS Autonomy

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Limited data bandwidth

Data bandwidth with Mars operations varies from 500 bps to 2Mbps depending on the availability of an relay assets and performance of the communications link.

Our questions

In the end, it is all about communication cadence and data volume that can be transmitted (a.k.a., downlinked) to Earth.

Intermittent communications

When can we communicate?

How often can we communicate?

How long can we communicate?

Delayed communications

How long we cannot communicate?

What level of autonomy should we allow for the Lander?

What decisions and activities should we allow for the Lander?

What decisions that must be made by the Ground team?

Limited data bandwidth

How much data can we receive?

Is it enough to make an informed decision?

How long would it take to receive all decisional data?

HSI-focused Modeling and Simulation

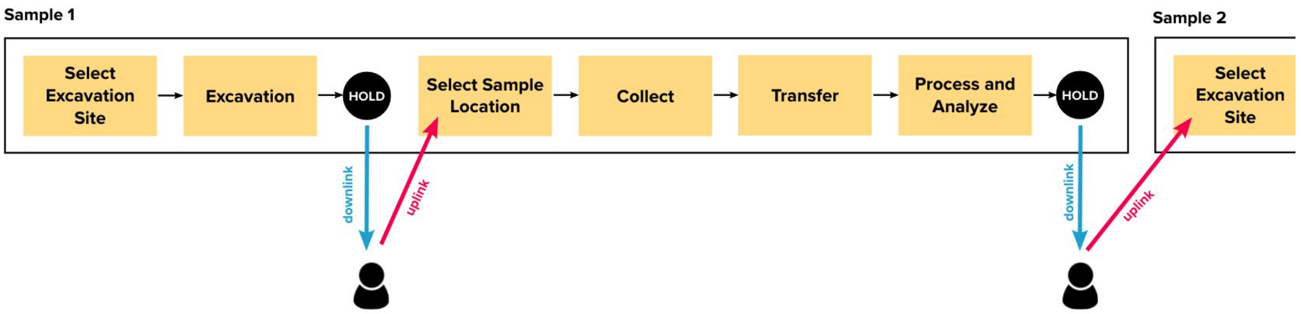
Defining design boundaries

Level of ground control over landers activities

GITL hold vs. GITL no-hold

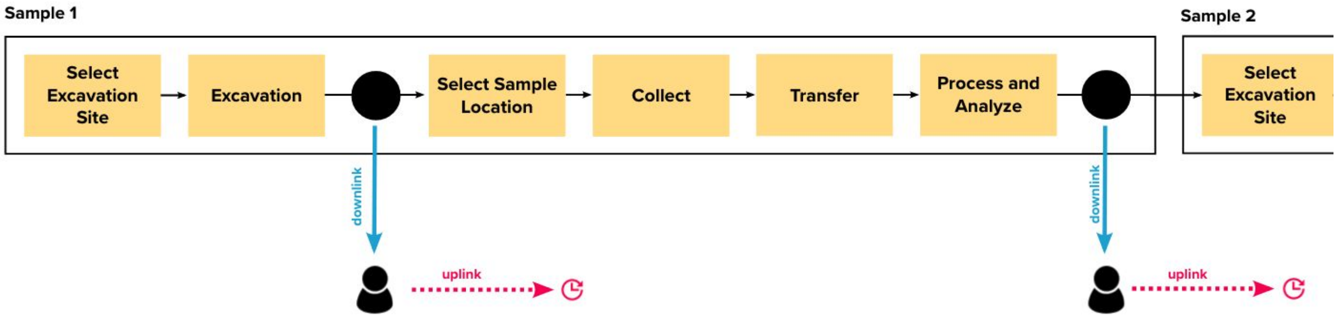
GITL (hold)

- Location of GITL opportunity intuitively tells you what you will be able to impact.
- Easy to conceptualize what ground will influence.



GITL (no-hold)

- Location of GITL opportunity only tells you when data will be downlinked
- It's unclear what you will be able to impact.



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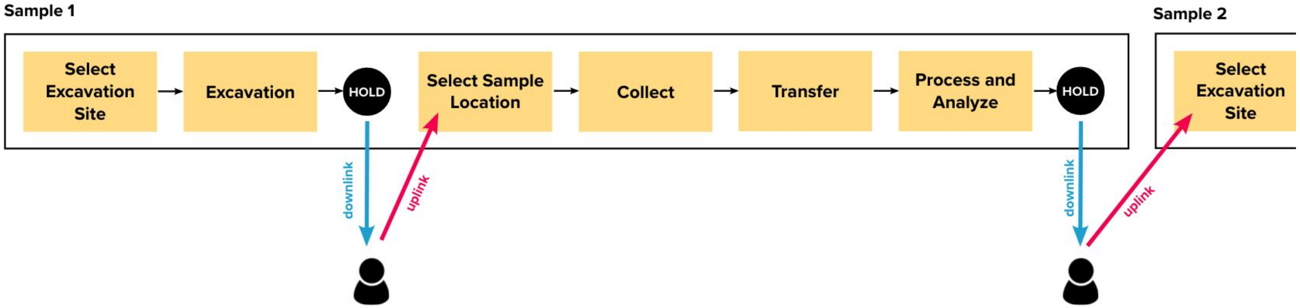
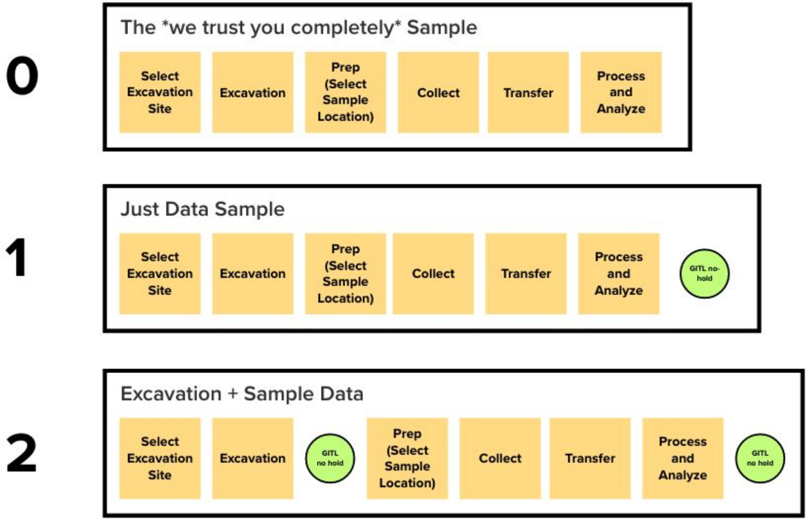
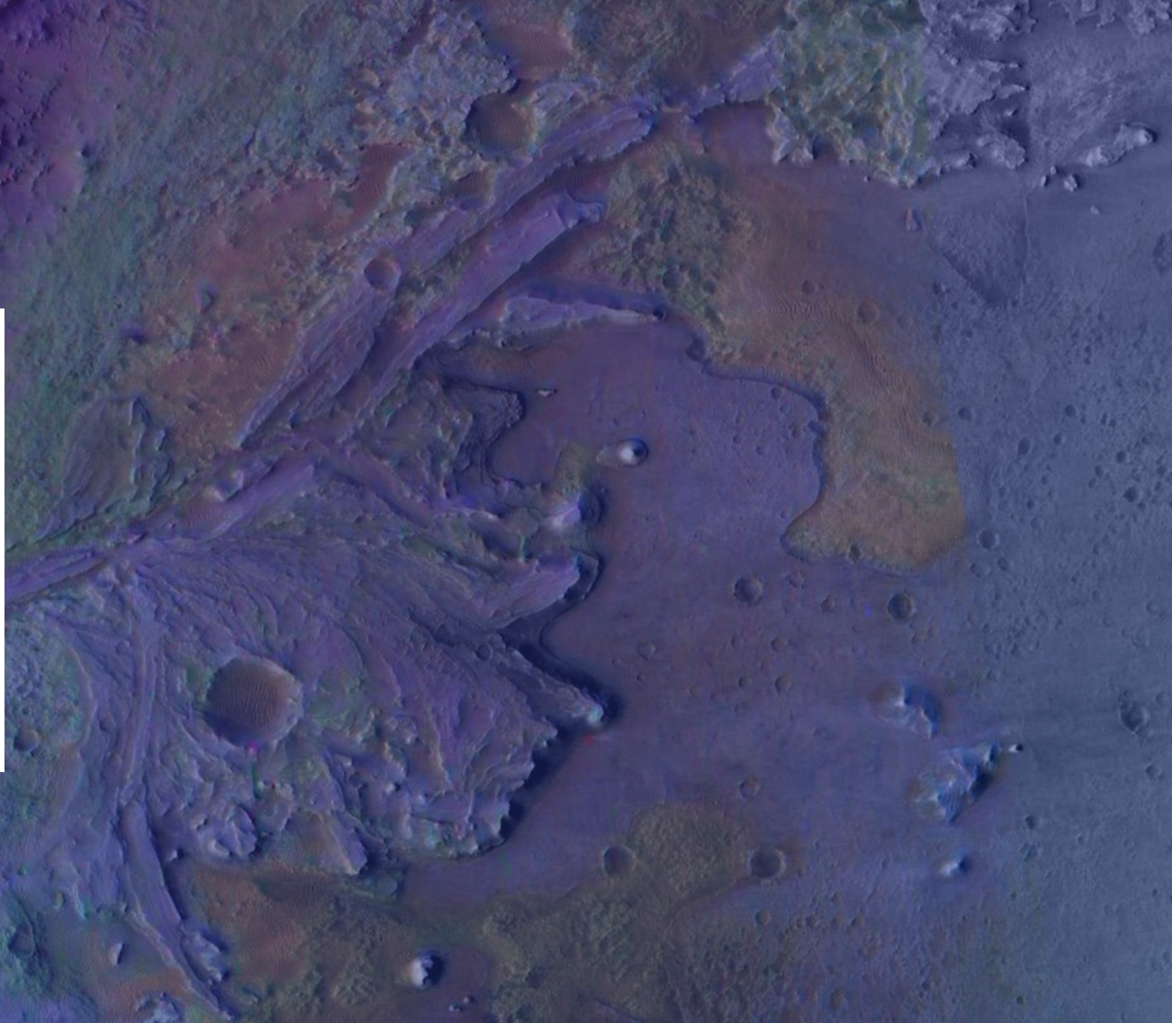


Most JPL's surface missions have operated this way.
The Ground Team has a very short leash on the spacecraft.

Number of Ground-In-The-Loop opportunities

- There is a morning and evening communication scheduled in addition to these communication opportunities.
- The assumption here is that no GITL is needed for engineering purposes. All scheduled GITL is for excavation and sample site selection.





Evaluating the design space

What metrics can we and should we measure to understand the effectiveness of a design option?

Q: How can we quantify **opportunity**?

A: Create a metric to measure “ground influence” on each major activity.

Q: How can we quantify cost?

A: Time spent sleeping, lost sample opportunities.

Metric 1: Ground Influence

Opportunity metric measuring how much influence ground could have over an activity.

A count of the number of uplinks that happen prior to an activity, weighted by the percentage of decisional data available on the ground with respect to total decisional data collected at the time of each uplink.

# Uplinks Prior	0	0	0	0	1	2	3	3	4	4	4	4	5
Ground Influence	0	0	0	0	0	0.8	1.7	1.4	2.3	2	1.8	1.6	2.5
Event Timeline	Excavate 1	Sample 1	Sample 2	Sample 3	Excavate 2	Sample 4	Sample 5	Sample 6	Excavate 3	Sample 7	Sample 8	Sample 9	Excavate 4

Uplink 1 Uplink 2 Uplink 3,4 Uplink 5,6 Uplink 7,8

Finding 3: Impact of GITL (no hold)

Night-Time Sampling	# GITL (no hold)	# Samples Collected	Avg. Influence Score
0 Sampling	2	9	1.5
	1	9	1.3
	0	9.5	0.6
1 Sample	2	10	1.6
	1	10	1.6
	0	10	0.3
∞ Sampling	2	11	1
	1	11	1
	0	11	0.1

no thermal constraints, 16hr excavations, positive result pattern

Adding GITL (no hold) opportunities has a:

- minimal impact on number of samples taken in comparison to the night-time sampling rules
- Can have a large impact on the ground influence score

A paper has been published. And let us know if you'd like to know more about it.

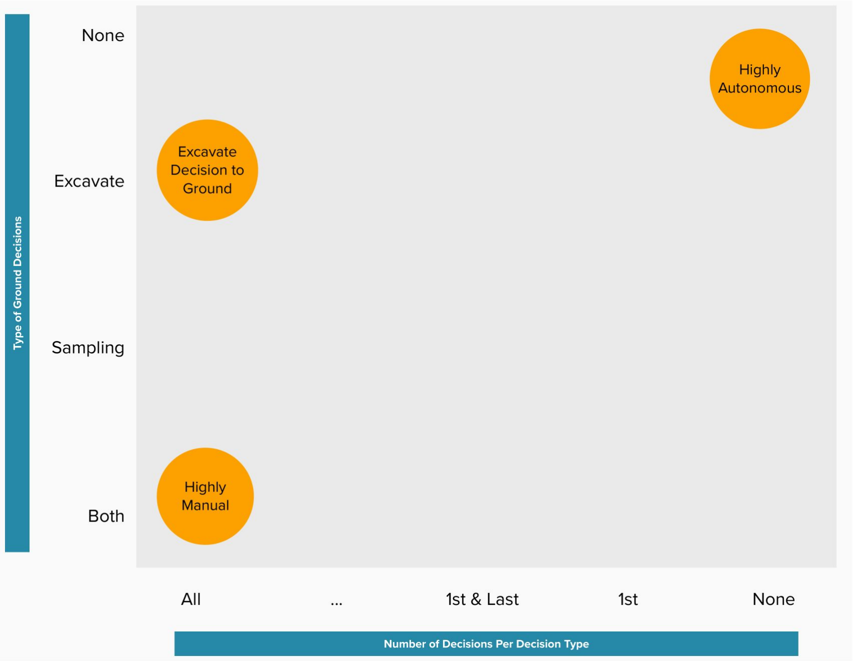
S. Y. Kim, A. Dhanushkodi, K. Roffo, G. Tan-Wang, S. Laubach and G. Reeves, "Ground-In-The-Loop Mission Concept Study for Europa Lander Using Modeling and Simulation," 2023 IEEE Aerospace Conference, Big Sky, MT, USA

What is the HSI approach here?

You look at **what communications opportunities** are there, and see what decisions the Ground team make/influence that's meaningful and valuable.

Or you look at **what decisions** that ground team should make and see what communications patterns are needed.

The key is both studies need to be tied to the **mission performance** at the end. And designing for the most optimized way.



Ground Decisions

We did look at the design space for types of ground decisions where we make the Lander to wait for the ground to communicate their intent back. (Ground in the loop with hold)

S. Y. Kim, A. Dhanushkodi, K. Roffo, G. Tan-Wang, S. Laubach and G. Reeves, "Ground-In-The-Loop Mission Concept Study for Europa Lander Using Modeling and Simulation," 2023 IEEE Aerospace Conference, Big Sky, MT, USA

Now we understand the design space and their effectiveness. What next?

Our conclusion is that our sweet spot is inserting 1 to 2 GITL and execute the mission. In theory, we can collect nine to 11 samples with better Ground influence on the collected samples.

What do you think we need to learn further?

Hint: The basis of operation paradigm is currently “do exactly what I say. If you can’t, call me and wait until I can tell you what to do.” So highly autonomous lander is something that they never have operated.

Our questions

Now it is all about understanding the autonomy enough that the ground can let go of its control and intervene when appropriate.

Highly Autonomous Lander

How do I let go of my control?

Do I trust that the Lander can do the job well?

Do I question every decision that the Lander makes?

Can the Lander understand what my intent is correctly?

Limited data bandwidth

What information and data do I need to have confidence in the Lander's decision?

How can I understand why the Lander make the decision that it makes?

Who operates the spacecraft, by the way?

Up to 200 members of the team in a given day

Spacecraft Ops

Instrument Ops

L

Science Ops

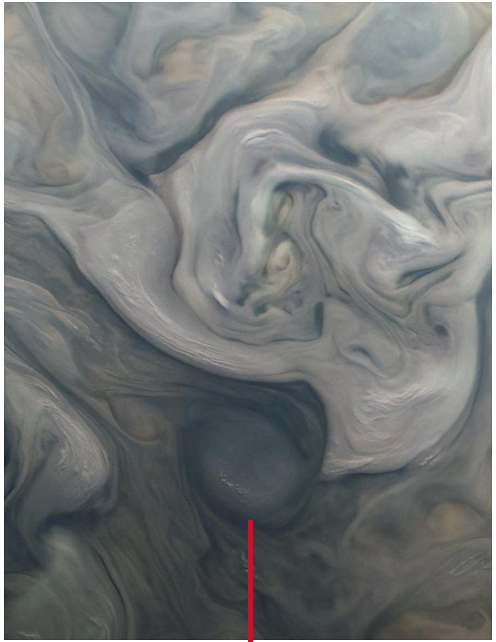
Science

On the landing day of Mars 2020

Clockwise order: Inside Mission Control, inside a mission support area, Perseverance Rover's Team in the EDL (Entry, Descent, Landing) War Room at NASA’s JPL all supporting the landing of Perseverance.

There are 200 people operating the Lander. How can we answer these questions?

How do we do when we have one operator as the human interacting with autonomy?
Do you think the methods and approaches are applicable here as well?

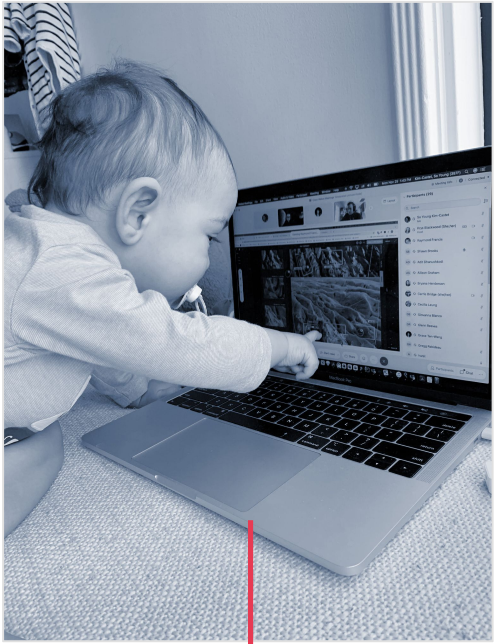


Swirling clouds on Jupiter are shown in an image taken by the JunoCam public engagement camera aboard NASA's Juno spacecraft on Feb. 25, 2022.

Design Simulation

Design Simulation is…

A role playing exercise in which real people pretend to be in operations with fake systems at some level of fidelity, for some duration.

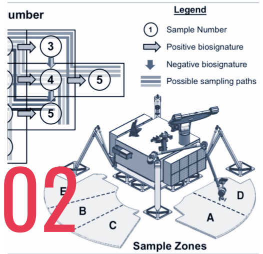


Great for finding out…

01

BEHAVIOR

How people will (actually) behave in a situation



02

CONOPS

Whether your concept of ops works

03

PROCESS

Whether you have the right process

04

INFO PRESENTATION

How to present the right information in the right way, at the right time.

What happens in a design sim?

Photo: Mars 2020 Design Simulation, the largest ever.

What happens in a design sim?

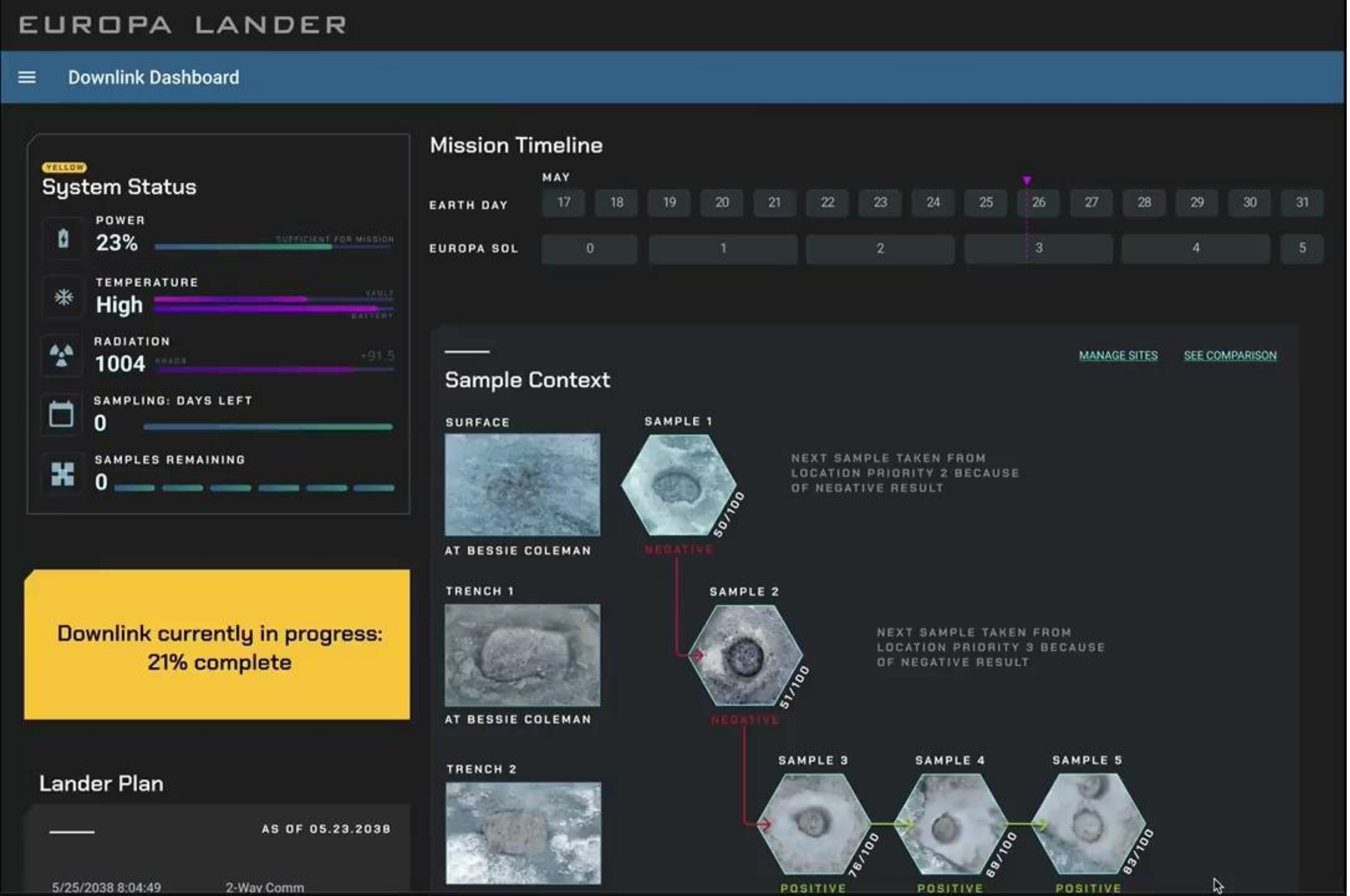
Europa Lander DesignSim; it was during the pandemic, all were virtually conducted.

Priming and Immersion

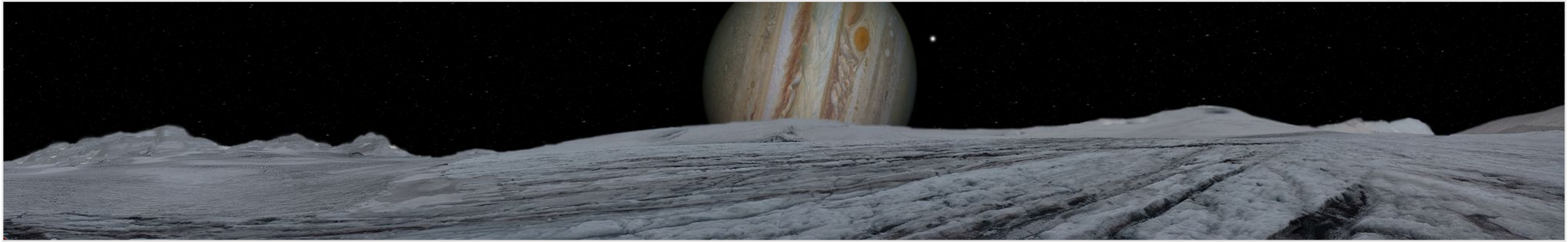
You need a concrete scenario to interrogate a hypothetical future.

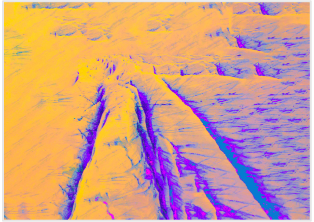
“Good morning. It’s 9am Monday, May 23rd 2038 and we are in the nikta (night) of Sol 0. Yesterday we had a perfect landing and all instruments checked out with no issues. Today while we take a look at the pictures and discuss the plan, Lander will be excavating its first two trenches.”

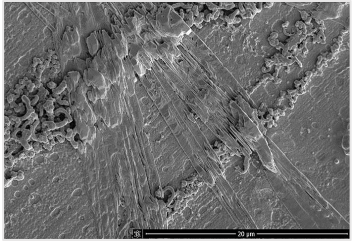
Examples of the immersive experience

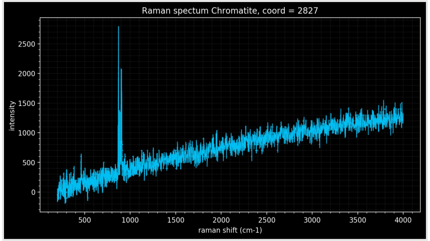


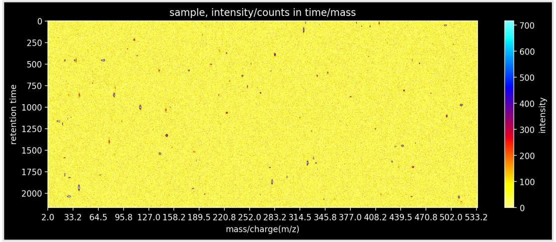
Simulated Data

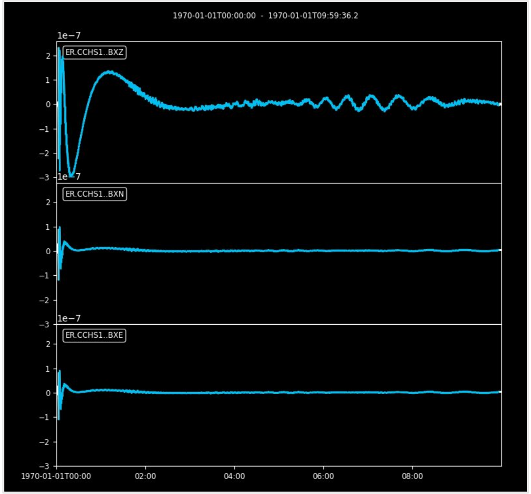










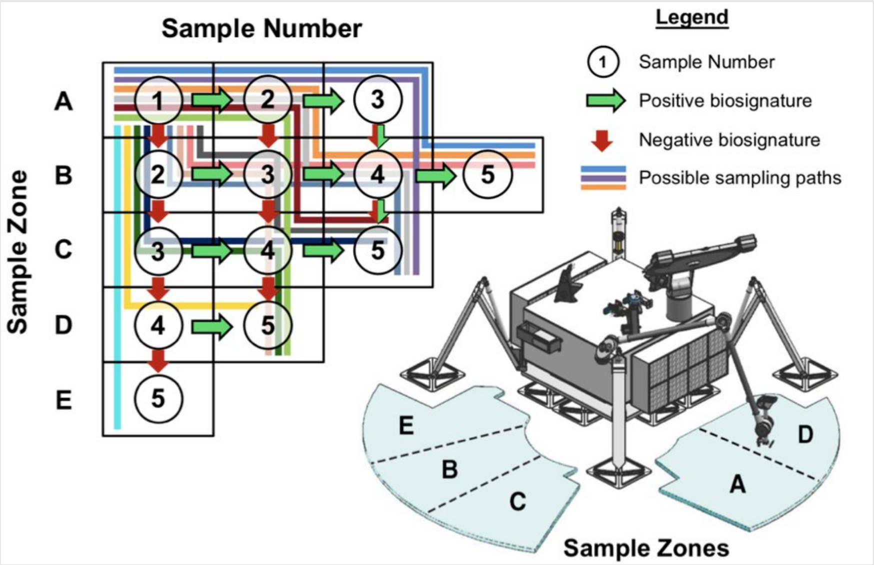


Timeline Simulation (Remember the earlier section?)

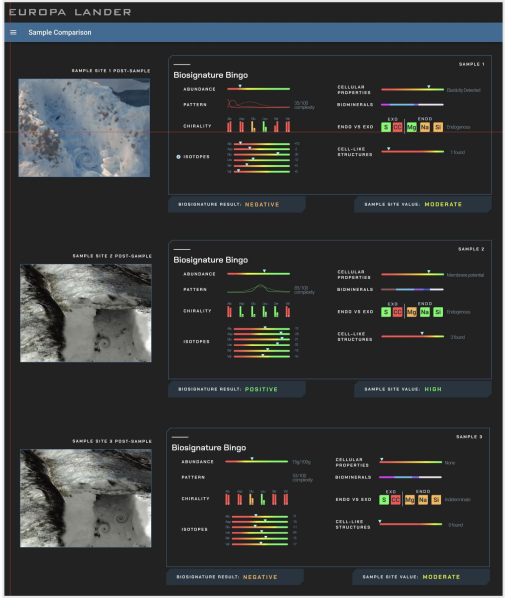
RAVEN is developed by MGSS for AMMOS. Mission model developed by the magical Kenny Roffo for Lander.

Design Sim 1: What's not working, What's missing

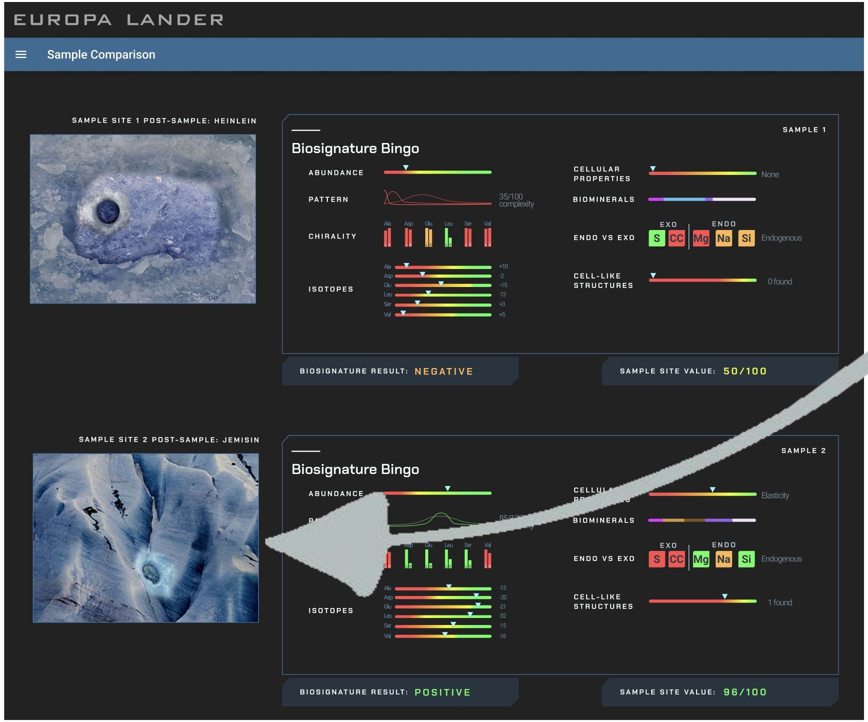
The one-way biosignature bingo path isn't what we need



We need the autonomy to rank and compare samples to each other.



Design Sim 2: Unexpected Ops team's need

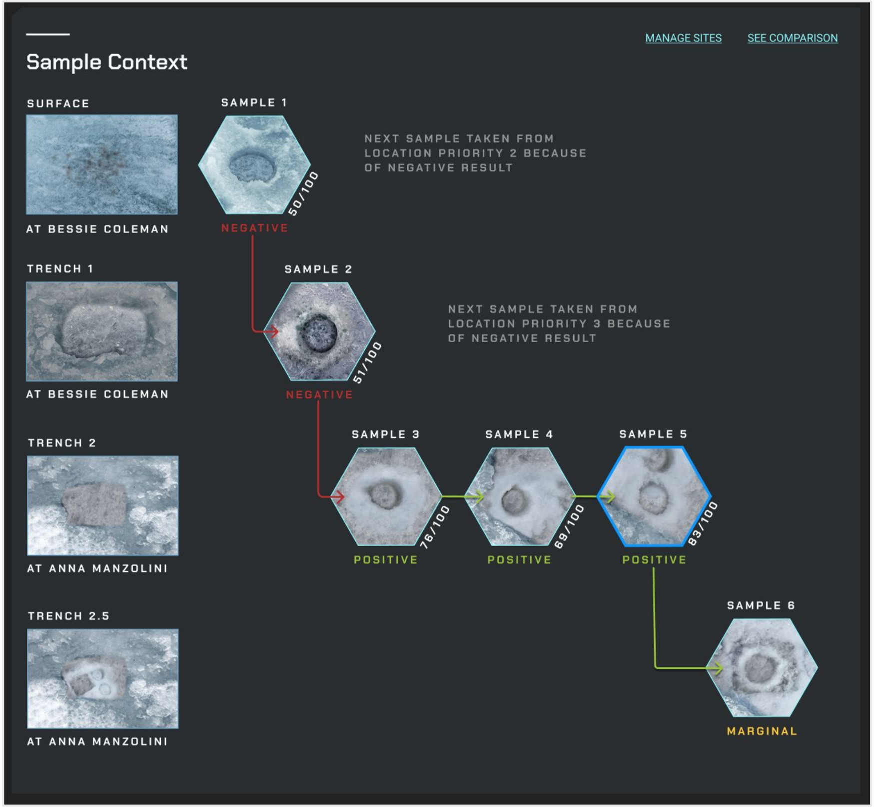


In 5 years, we've never discussed sampling the surface. Not once.

SURFACE Sample?!?

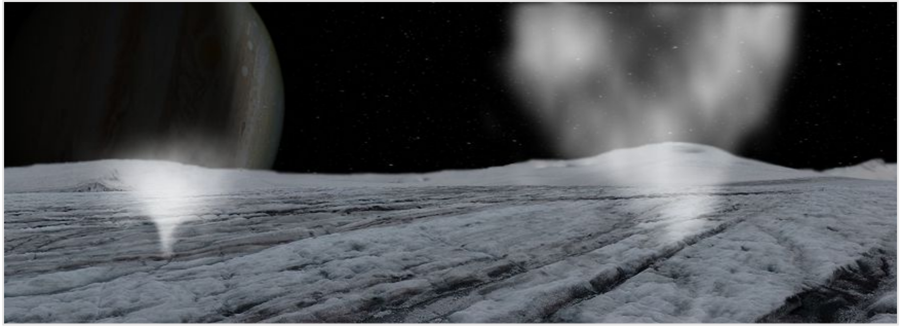
could never have predicted, we need to be able to evolve the algorithm.

Design Sim 3: Detailed definitions and specification



Learned the real definitions of data and needs

Science priorities change with new discoveries



Discover use cases that change everything

Flight system requirements: multispectral?

Return to a negative biosignature bingo site

Compare samples to each other

The importance of a utility score

Sample the surface

Data curation is more nuanced than we realized

Change our mind about what data is classified as decisional, mandatory, residual

Get ahead of the development curve

Tested the conops in pre Phase A

Got to experiment with what-ifs for conops

Early (initial) set of requirements for ground tools
With your first set of UX designs and usability tests!

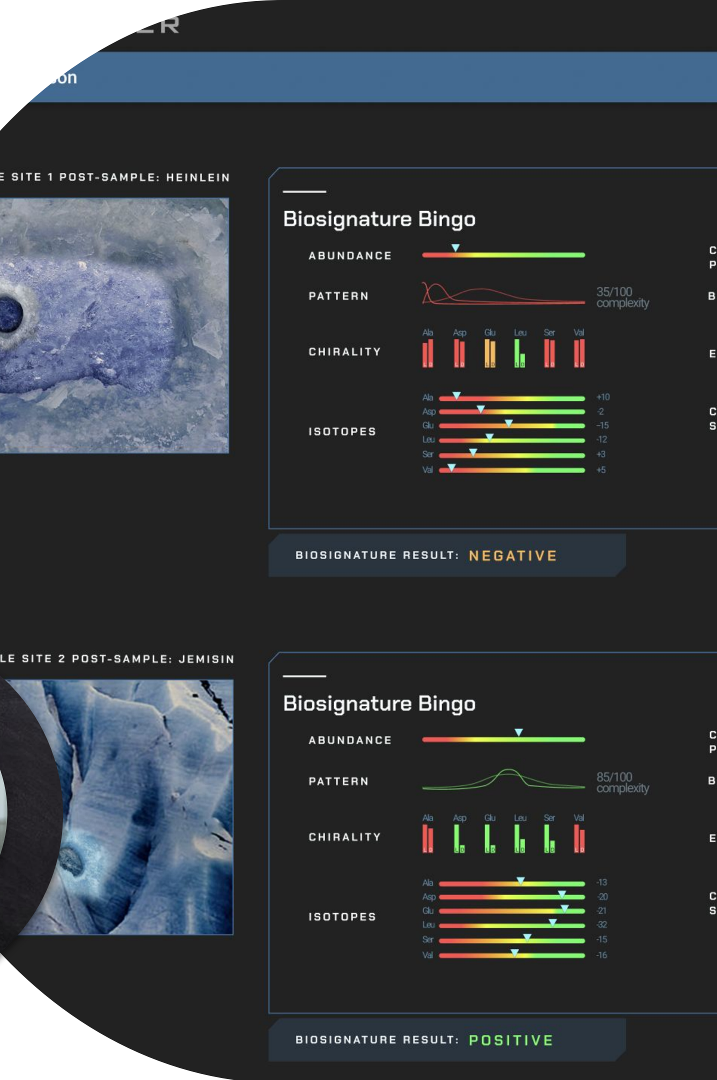
Early requirements for autonomy

Early training benefits - both informs training and gives you a jump start

Its impact to the project is

Influencing instrument requirement, autonomy capability requirement, etc.

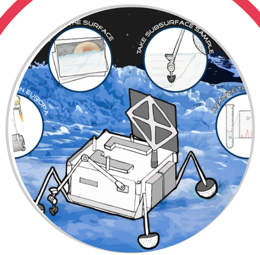
And many more - request a design simulation talk to learn more about it to **Krys Blackwood,** Principle Human-Centered Designer at JPL.



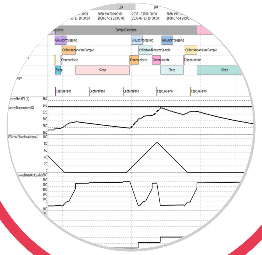
Reviewed and determined not to contain CUI.

At a glance

How HSI activities and supports were incorporated into the project



Scenario Development



Modeling & Simulation

Design Simulation

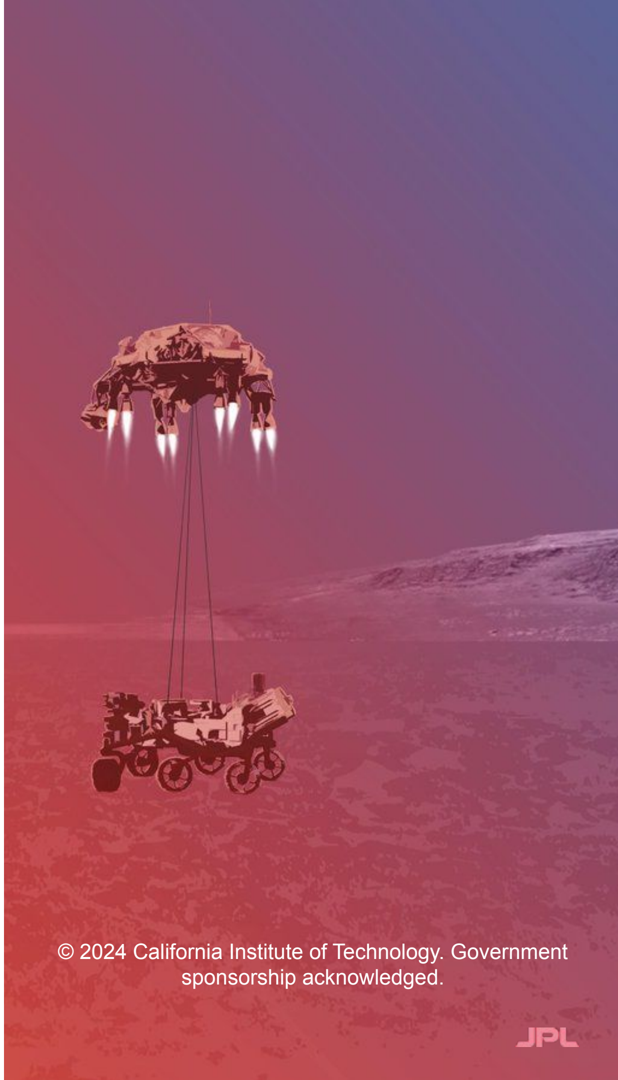
ConOps Development

System Design

Discussion

How would you go about your work?

Any particular inspiration for your domain of work?



Jet Propulsion Laboratory
California Institute of Technology