HYBRID CFD ENGINEERING MODEL OF PLUME INDUCED EROSION AND CRATER FORMATION DURING DESCENT OF LUNAR LANDERS

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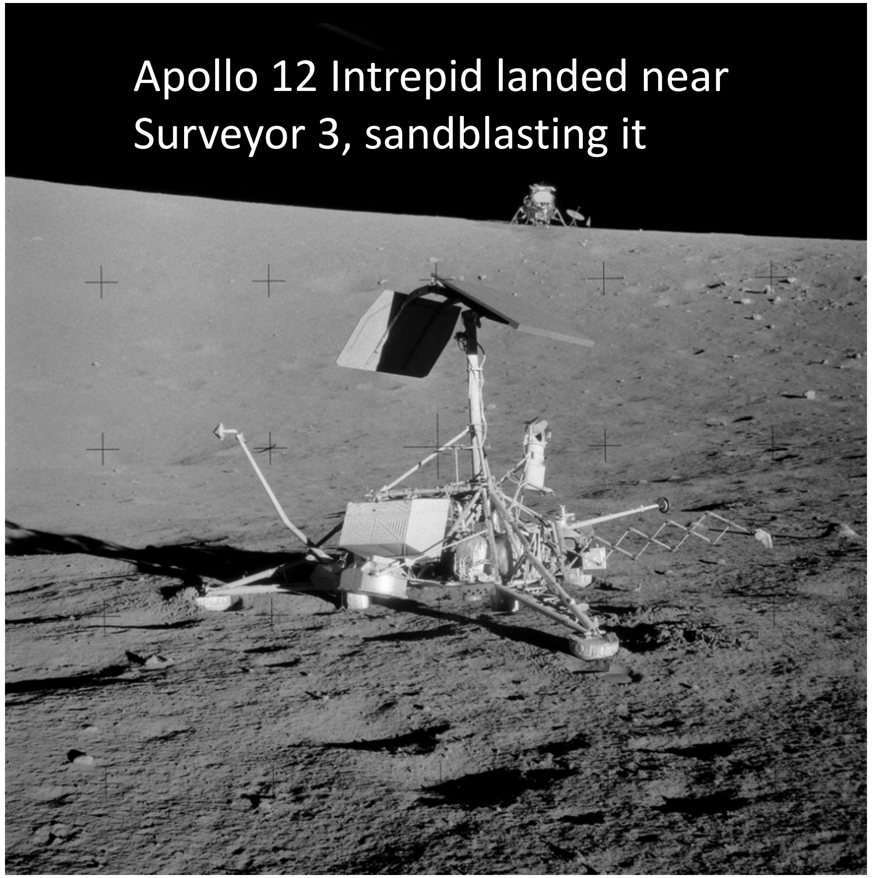
Introduction

- Plume Surface Interaction (PSI) involves complex physics that have the potential to drive mission success / failure
- Primary physics involved are:
  1) Plume flow alteration
  2) Cratering
  3) Ejecta
- Several lunar (Apollo) and Martian missions have documented PSI effects that could have drastically impacted the success of the mission
  - Landing blind (top image),
  - Dust in modules
  - Particle impact on vehicles and other assets (lower image)
- <u>NASA is returning to the moon</u> with both unmanned and manned landers. There is an *undefined risk* when it come to PSI for these landings.
- Engine power levels and configurations have varying PSI effects that need to be quantified to protect the landers, the people and science equipment on them, and other vehicles and structures on the surface

PSI dust obscures view of Apollo landing site



Apollo 12 Intrepid landed near Surveyor 3, sandblasting it

Background

- Computational Fluid Dynamics (CFD) capabilities for simulating PSI capabilities are maturing

- NASA Marshall Space Flight Center's propulsion fluid dynamics branch has a suite of existing and in-development tools for predicting PSI effects
  - Gas Granular Flow Solver (GGFS) – High fidelity multi-phase tool that directly simulates granular media (soil/regolith) interacting with rocket plume gas
    - Too computationally expensive for simulating entire descent trajectory quickly for engineering design decisions

  - Descent Interpolated Gas Granular Erosion Model (DIGGEM) – Engineering model of viscous crater formation which requires shear stress maps (from CFD) as inputs

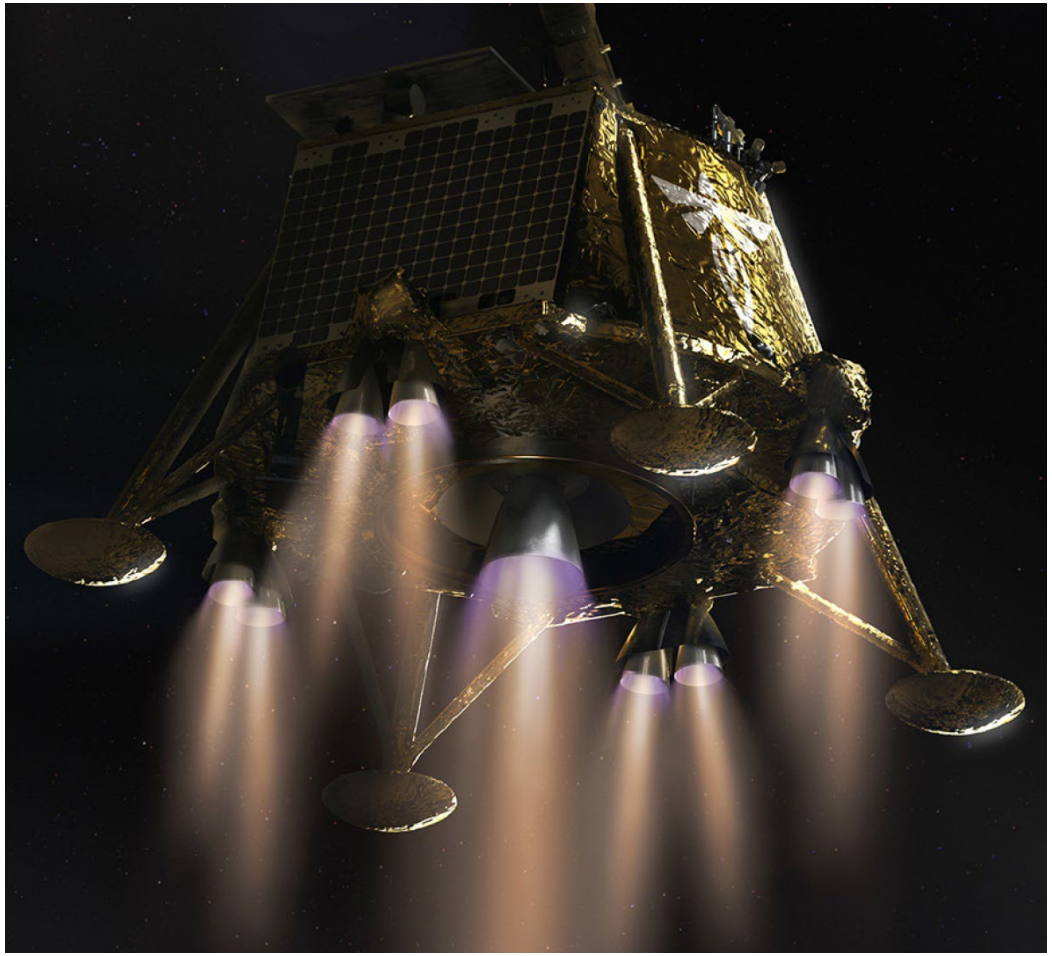
  - Loci/CHEM-DIGGEM – Hybrid CFD/Engineering model simulates gas phase and models crater formation due to viscous erosion from impinging plume

  - Static Porous Media (SPM) – Model of gas diffusion into non-deforming granular media for predicting onset of fluidization/diffusion-driven-flow

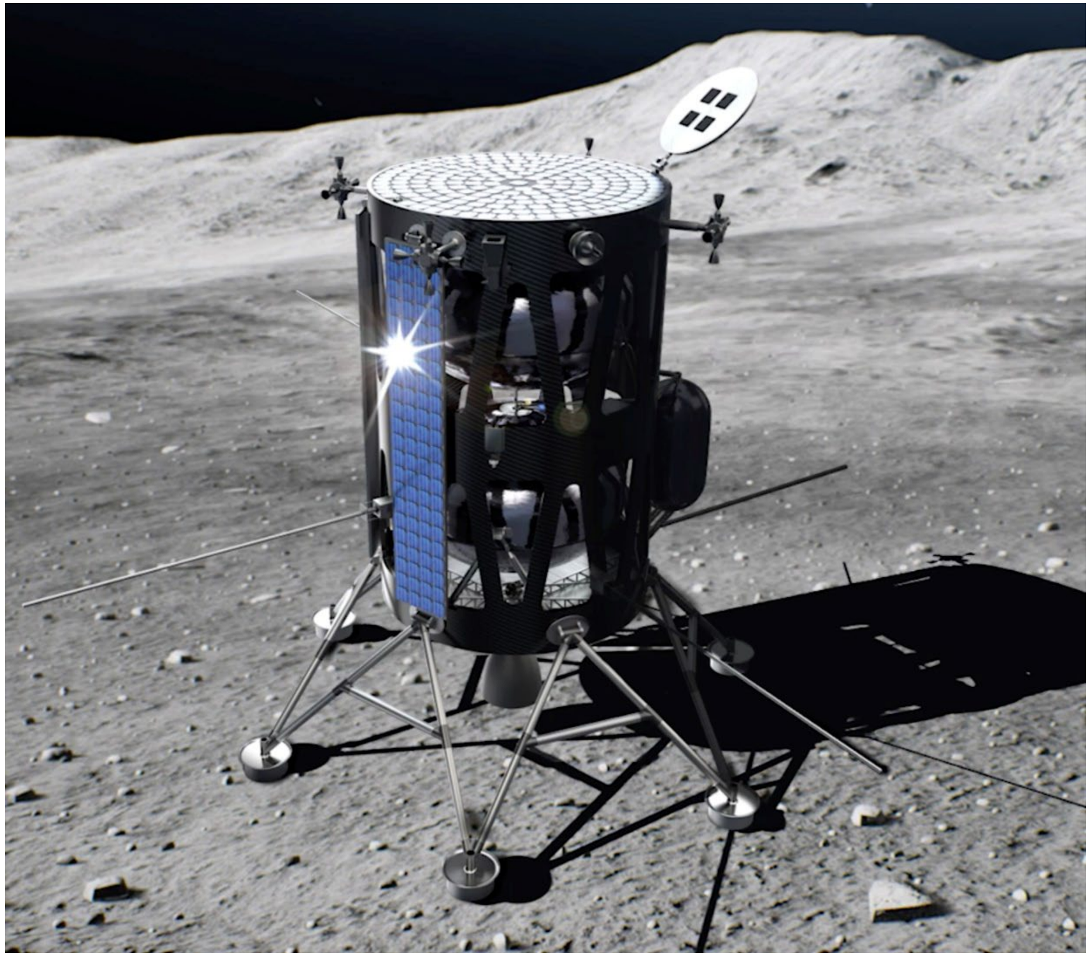
Background

Commercial Lunar Payload Services (CLPS) Landers Present an opportunity for application and maturation/improvement of PSI erosion modeling capabilities

Firefly Blue Ghost

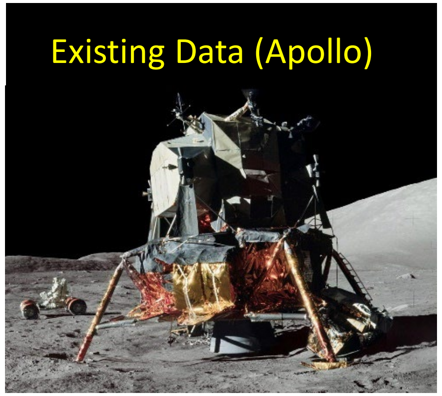


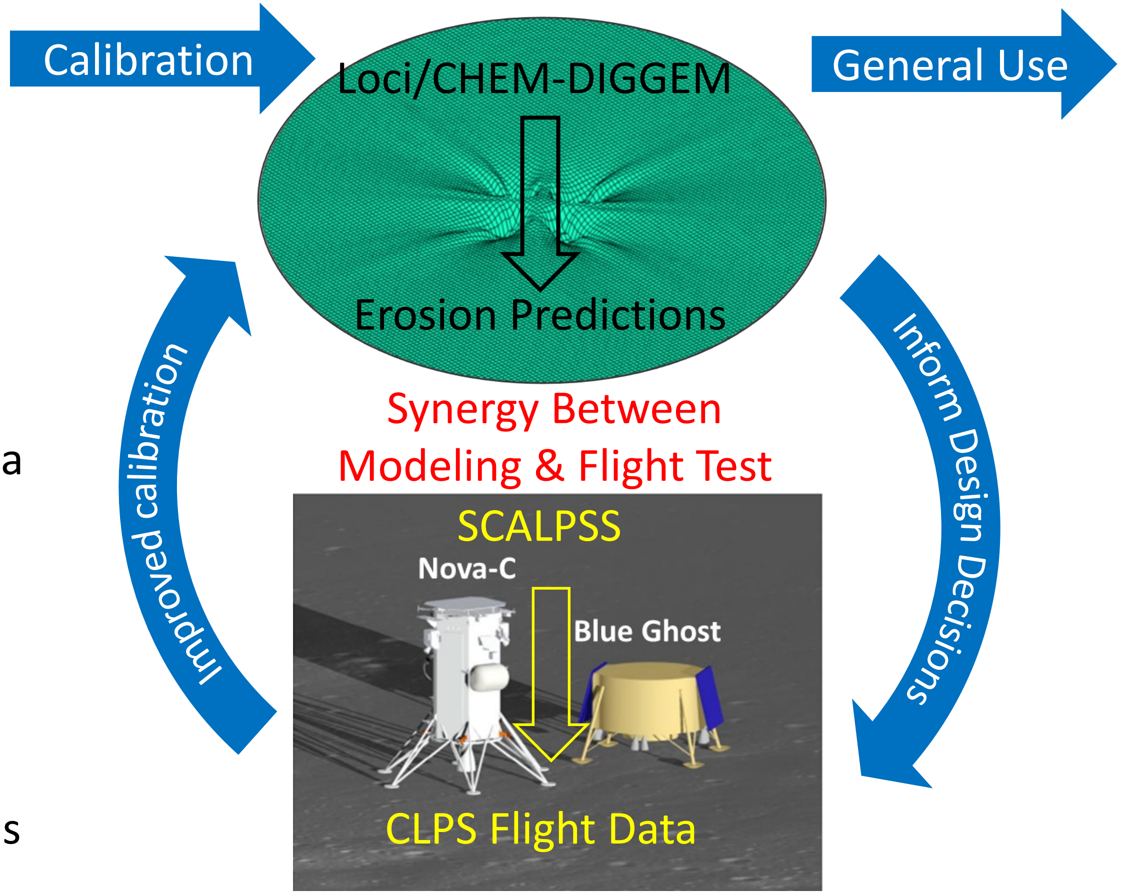
Intuitive Machines Nova-C



Background

- The Stereo Camera for Lunar Plume-Surface Studies (SCALPSS) project is putting cameras on CLPS landers to observe and quantify PSI effects.
- SCALPSS will produce validation data for models, but needs modeling predictions to inform design decisions and CLPS placement

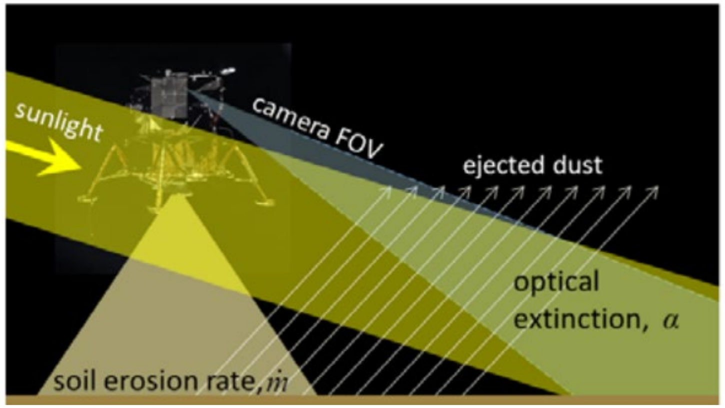


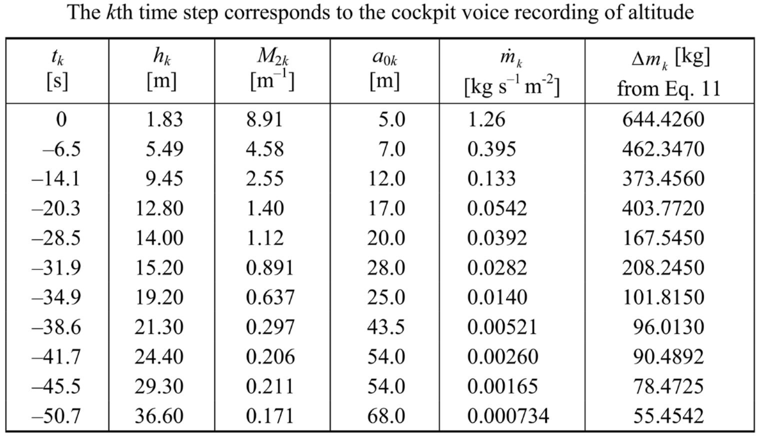


- Erosion models first calibrated using sparse Apollo data
- Erosion model predictions inform SCALPSS design and placement on CLPS landers
- As SCALPSS flies on CLPS missions, it will generate additional flight data which can improve DIGGEM calibration
- Loci/CHEM-DIGGEM can be used for other applications at any time

Calibrating Model With Apollo Data

- Lane and Metzger[1] used optical extinction method to determine soil erosion rate from Apollo images - similar to rainfall rate measurements from radar reflectivity



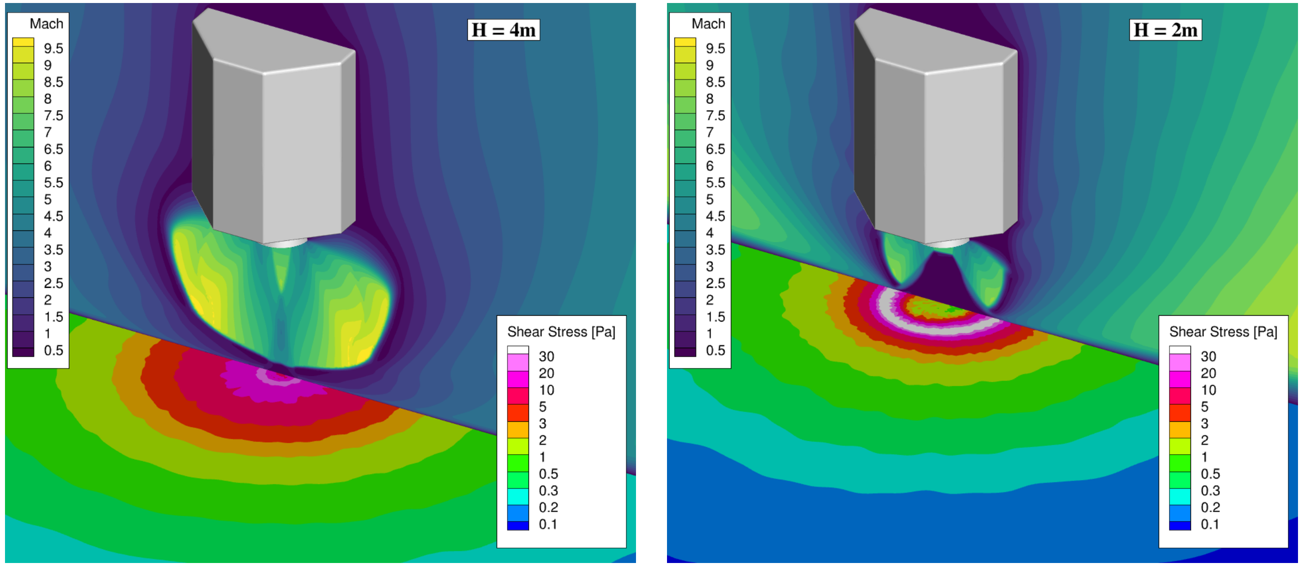


The kth time step corresponds to the cockpit voice recording of altitude

t_k [s]	h_k [m]	M_{2k} [m^{-1}]	a_{0k} [m]	$\dot{m}_k$ [kg s^{-1} m^{-2}]	Δm_k [kg] from Eq. 11
0	1.83	8.91	5.0	1.26	644.4260
–6.5	5.49	4.58	7.0	0.395	462.3470
–14.1	9.45	2.55	12.0	0.133	373.4560
–20.3	12.80	1.40	17.0	0.0542	403.7720
–28.5	14.00	1.12	20.0	0.0392	167.5450
–31.9	15.20	0.891	28.0	0.0282	208.2450
–34.9	19.20	0.637	25.0	0.0140	101.8150
–38.6	21.30	0.297	43.5	0.00521	96.0130
–41.7	24.40	0.206	54.0	0.00260	90.4892
–45.5	29.30	0.211	54.0	0.00165	78.4725
–50.7	36.60	0.171	68.0	0.000734	55.4542

CFD used to simulate plume flowfield at various altitudes.

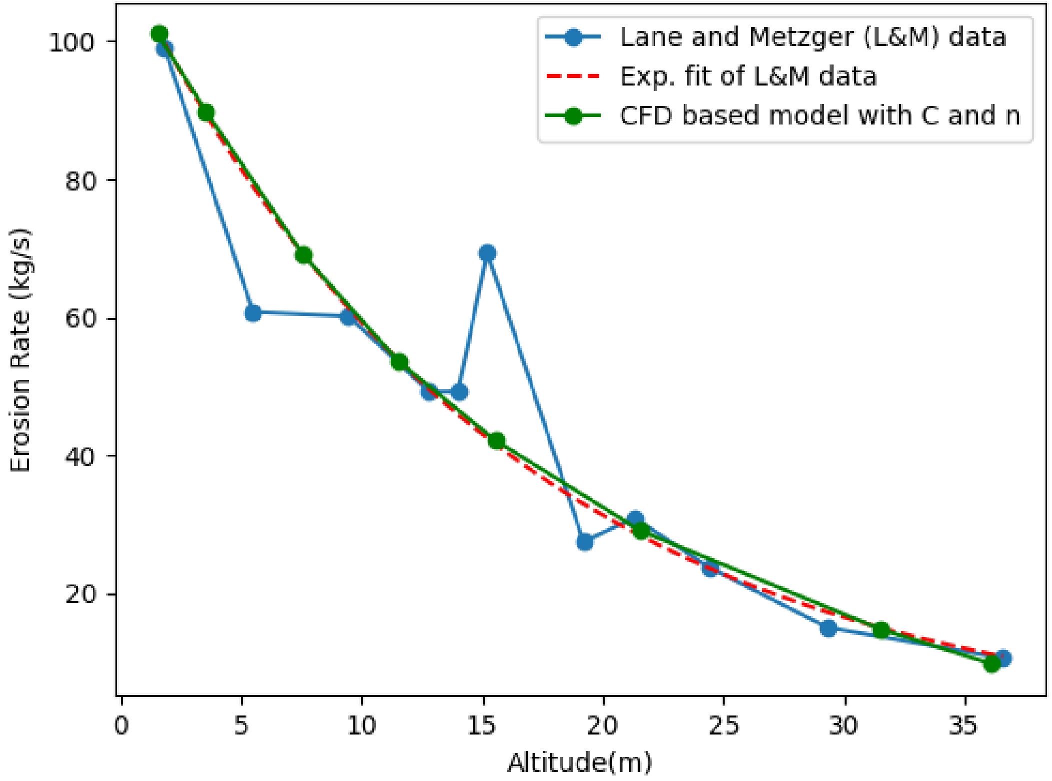
Flowfield is used as input to engineering erosion model DIGGEM (Descent Interpolated Gas Granular Erosion Model)



[1] *J. E. Lane and P. T. Metzger: "Estimation of Apollo lunar dust transport using optical extinction measurements." Acta Geophysics, Volume 63, Issue 2, (2015).*

Calibrating Model With Apollo Data

Erosion rate predictions at each altitude are compared to Apollo data from Lane and Metzger. Model parameters are calibrated to get best fit to Apollo Data



The calibrated model is then used to predict crater growth for CLPS (and other) landers

Engineering model of local erosion rate as a function of local shear stress

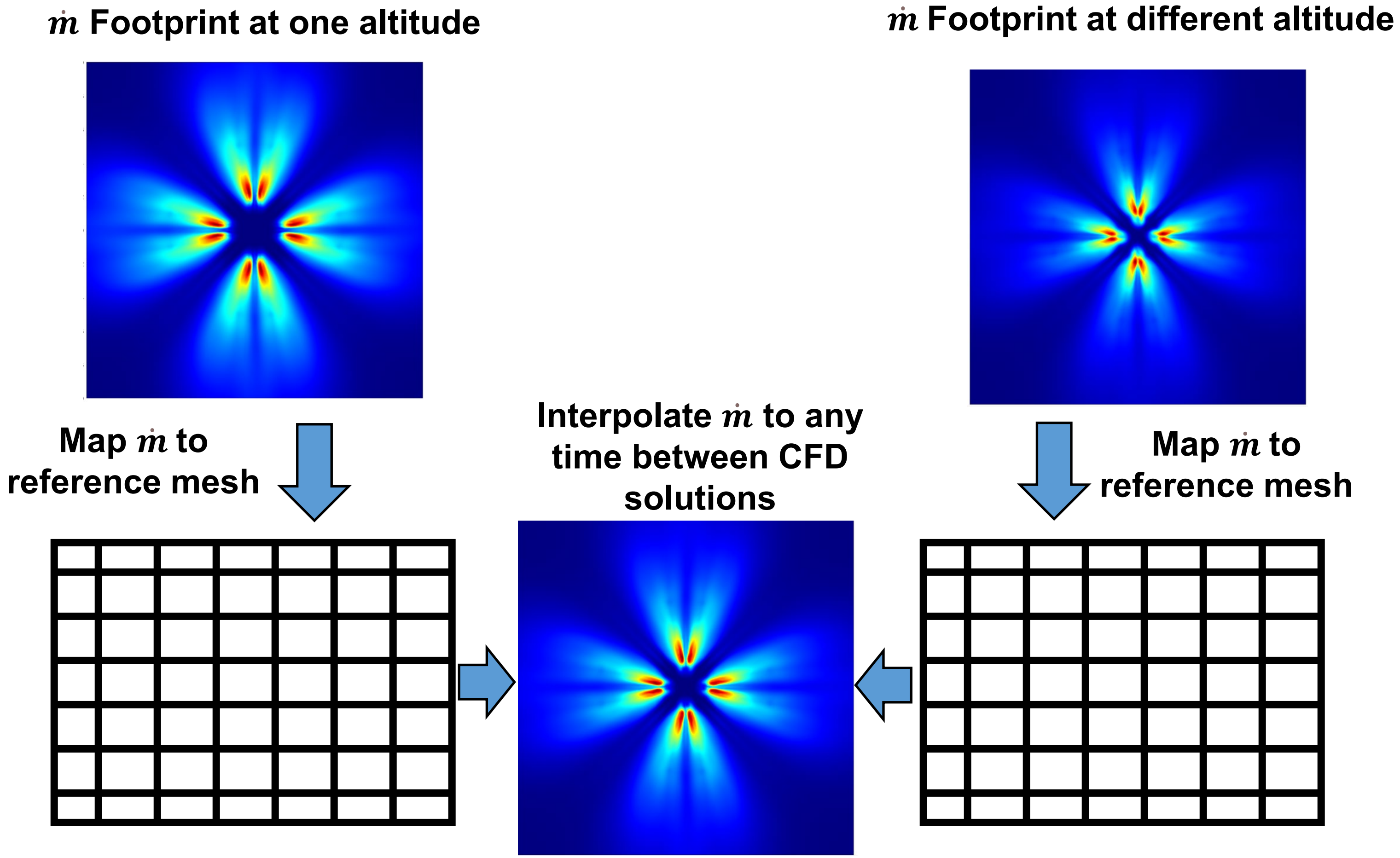
$$\dot{m}(x,y,t) = C\left(\tau(x,y,t) - \tau_{threshold}\right)^{n}$$

The local shear stress was calculated using CFD at fixed altitudes

These model parameters were calibrated using the erosion data derived from Apollo landing video

DIGGEM Model Advancement

The original DIGGEM model was applied as a post processing step to predict crater growth from results of several stationary CFD simulations at fixed altitudes



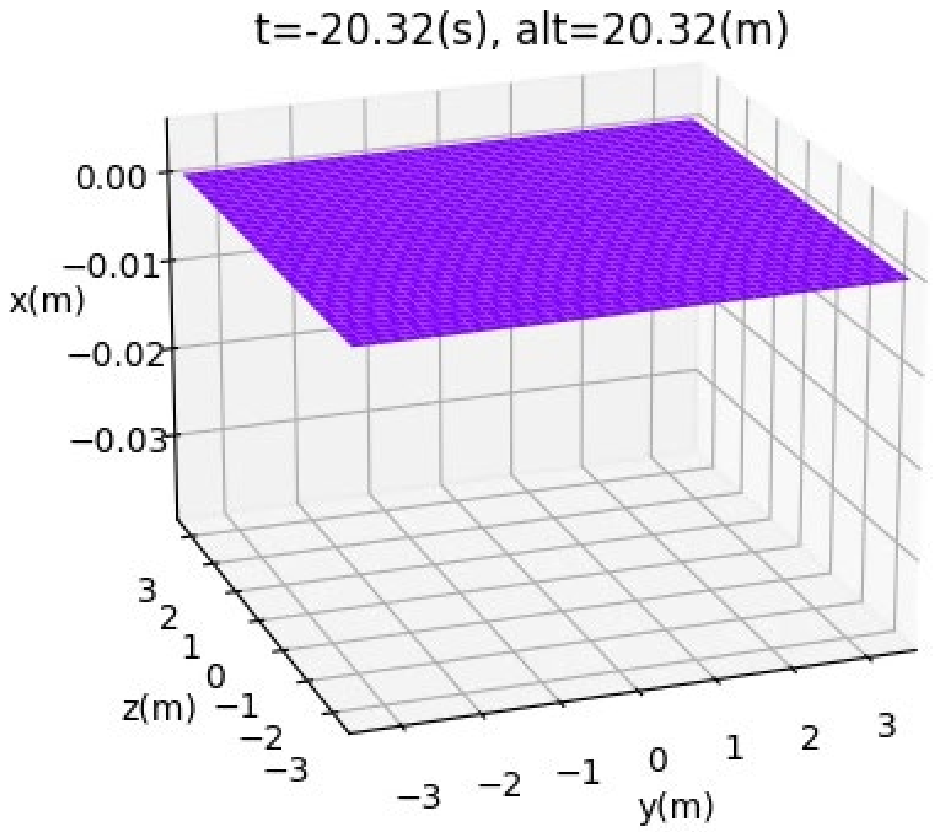
$\dot{m}$ Footprint at one altitude

$\dot{m}$ Footprint at different altitude

Map $\dot{m}$ to reference mesh

Interpolate $\dot{m}$ to any time between CFD solutions

Map $\dot{m}$ to reference mesh



Blue Ghost crater depth simulation

PFGT Erosion Prediction Comparison

Available data from scaled ground testing (Physics Focused Ground Test, PFGT) was used to validate model

Video of subscale ground test overlaid with DIGGEM prediction of crater

DIGGEM Model Limitations

- One way coupled – does not allow altered terrain shape to influence flow field/shear stress

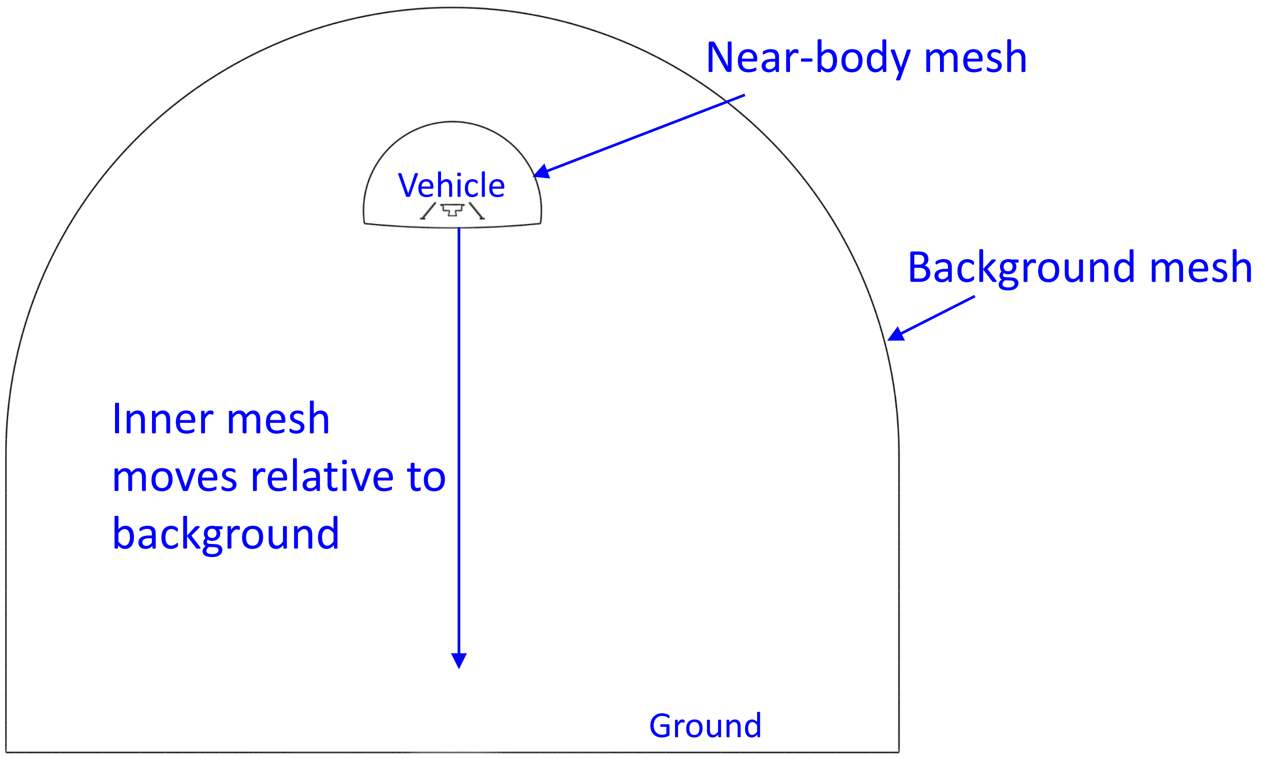
- Requires results from several CFD simulations at fixed altitudes as input (time consuming to generate)
    - No foreknowledge about which altitudes require simulation to capture meaningful physics

- Intermediate altitude shear stress is interpolated from simulated altitudes – results dependent on which altitudes are simulated

Loci/CHEM-DIGGEM Implementation

Now, erosion model has been implemented in Loci-CHEM-DIGGEM to allow fully coupled calculation of erosion with vehicle moving through descent phase

componentMotion module



Near-body mesh

Vehicle

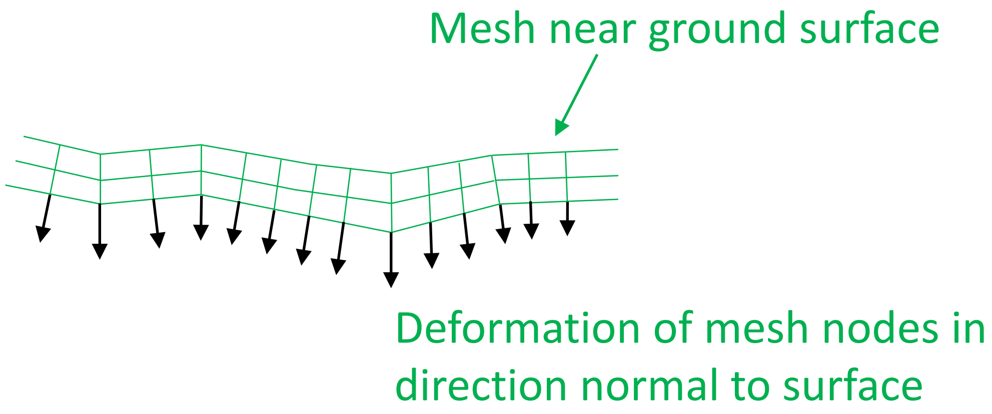
Background mesh

Inner mesh moves relative to background

Ground

Allows vehicle to move and approach ground during simulation by using dynamic hole cutting and an interpolation boundary condition

gridMotion module



Mesh near ground surface

Deformation of mesh nodes in direction normal to surface

sufaceErosionFlux module

$$\boxed{d = -[C\,(\tau - \tau_{threshold})^{n}/\rho]dt}$$

Specifies deflection used in the gridMotion module at each timestep to be a function of the local shear stress and regolith/soil density (same as in DIGGEM)

Loci/CHEM-DIGGEM Implementation

Need for Time Compression Approach

Descending Vehicle PSI problem contains widely differing timescales

- Vehicle descent occurs over tens of seconds with surface regression velocities of mm/s
- Plume flow has unsteady fluctuations that require microsecond resolution and velocities of km/s

Resolving the plume unsteadiness with 10^{-5}s timesteps and simulating a full 30s descent trajectory

- Requires 3,000,000 timesteps
- ~2 years of computation even when using thousands of processors

Solution: Compress many fluid flow timesteps into each vehicle motion and erosion timestep

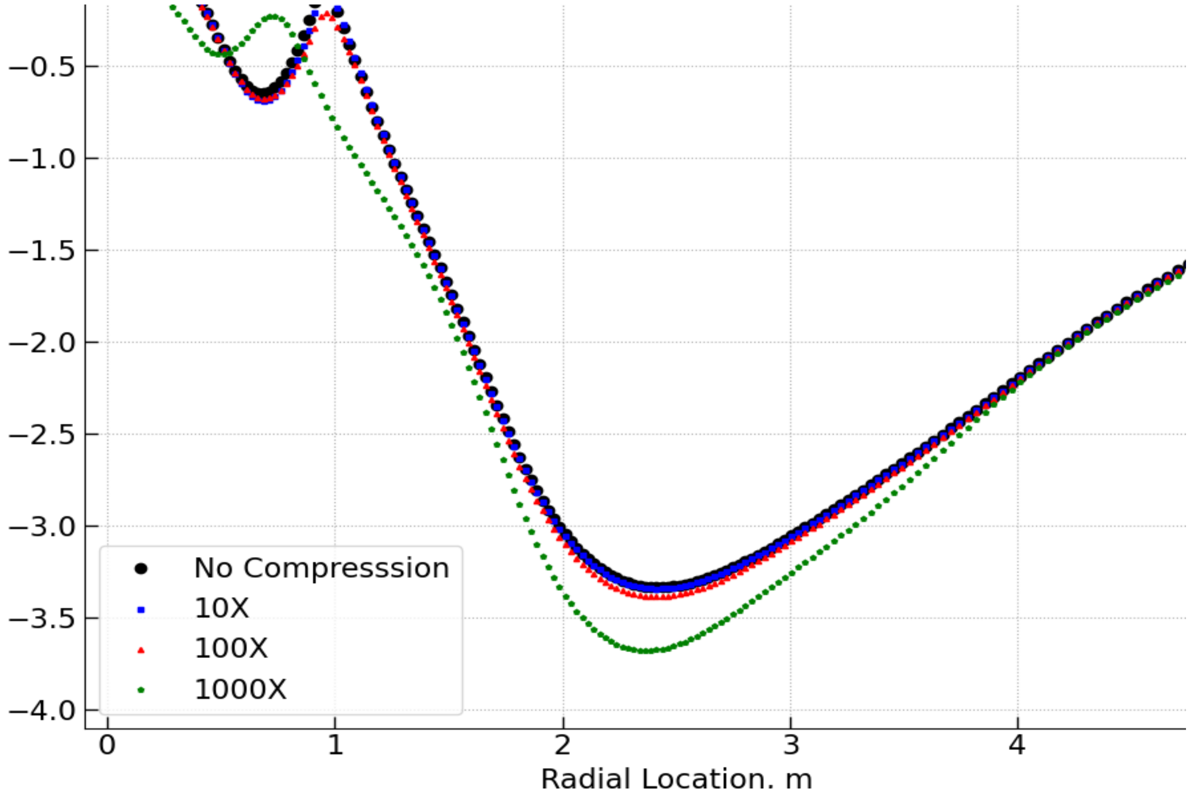
Loci/CHEM-DIGGEM Implementation

100X Time Compression Approach

- Multiply vehicle velocity and erosion rate by a factor of 100 to accelerate these timescales with respect to fluid flow
- Good approximation if result is independent of the compression factor used

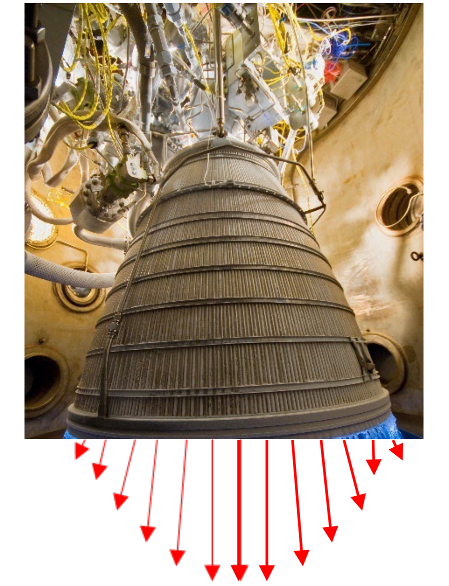
- Verified on simplified axisymmetric problem
- Compared crater profile after 5s of simulated time using various compression factors

10x and 100x compression produce almost the same crater profile as the uncompressed simulation

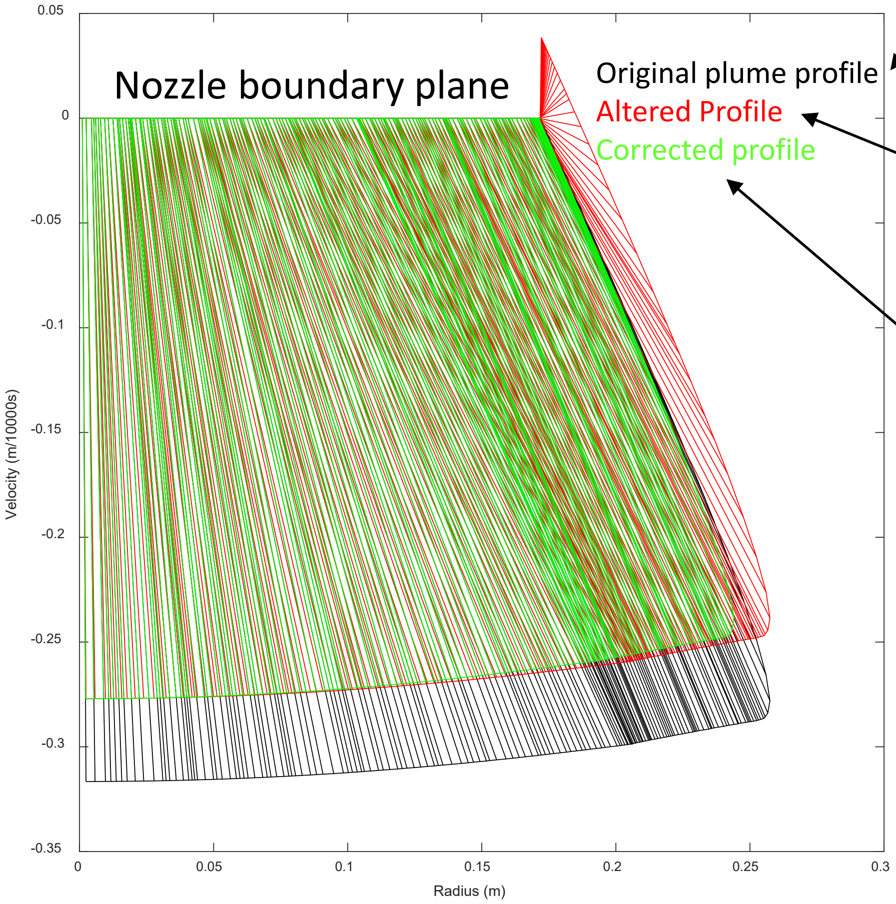


Loci/CHEM-DIGGEM Implementation

Corrected Nozzle Exhaust Profile



Exhaust velocity profile



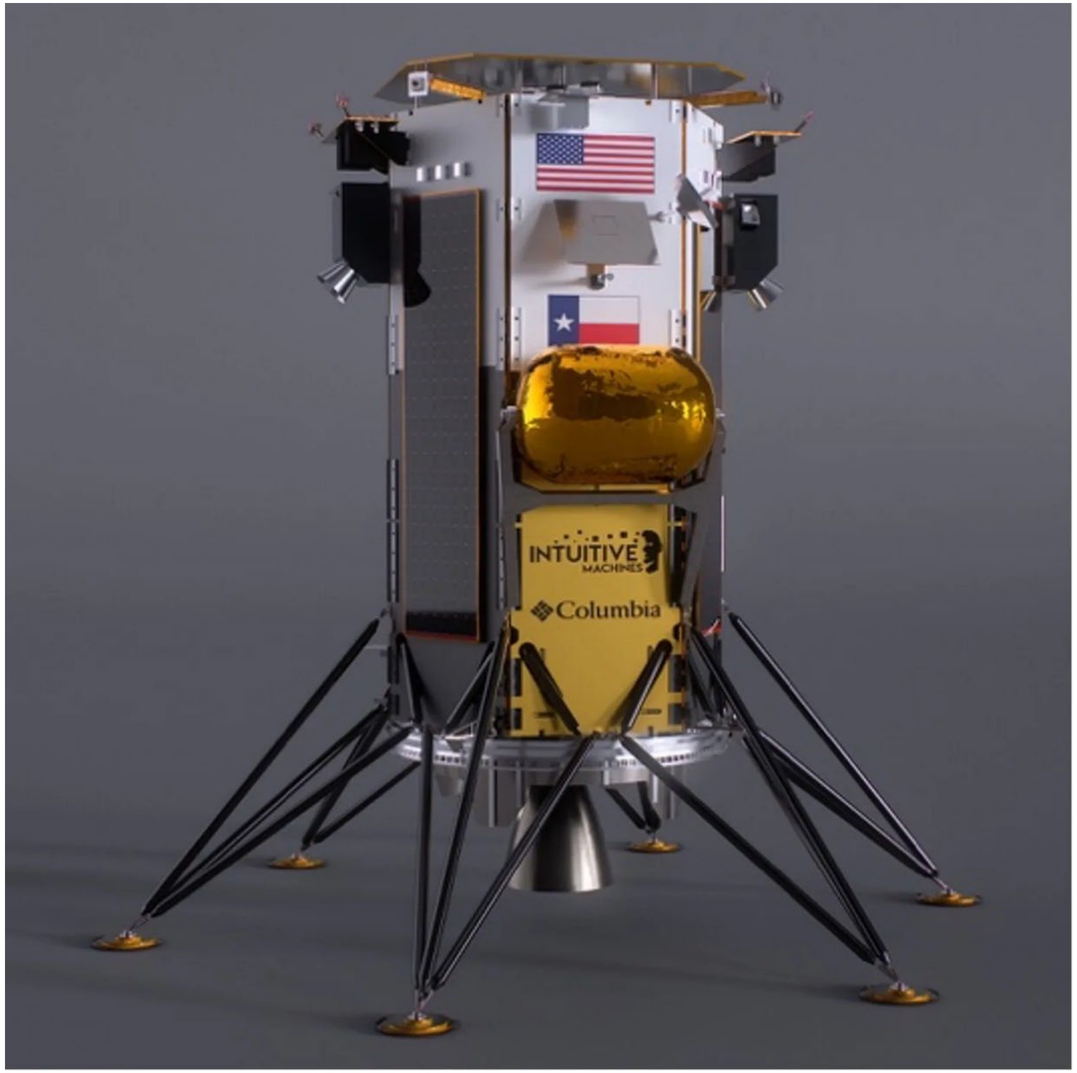
- 100x time compression introduces error in exhaust velocity profile because of artificially fast vehicle motion (exhaust velocity relative to ground is too high)
- Profile can be altered by subtracting off excess vehicle velocity
- Finally, profile can be corrected to preserve original engine thrust

Exhaust profile correction removes up to 10% error in apparent thrust

CLPS TO2-IM: Intuitive Machines Nova-C

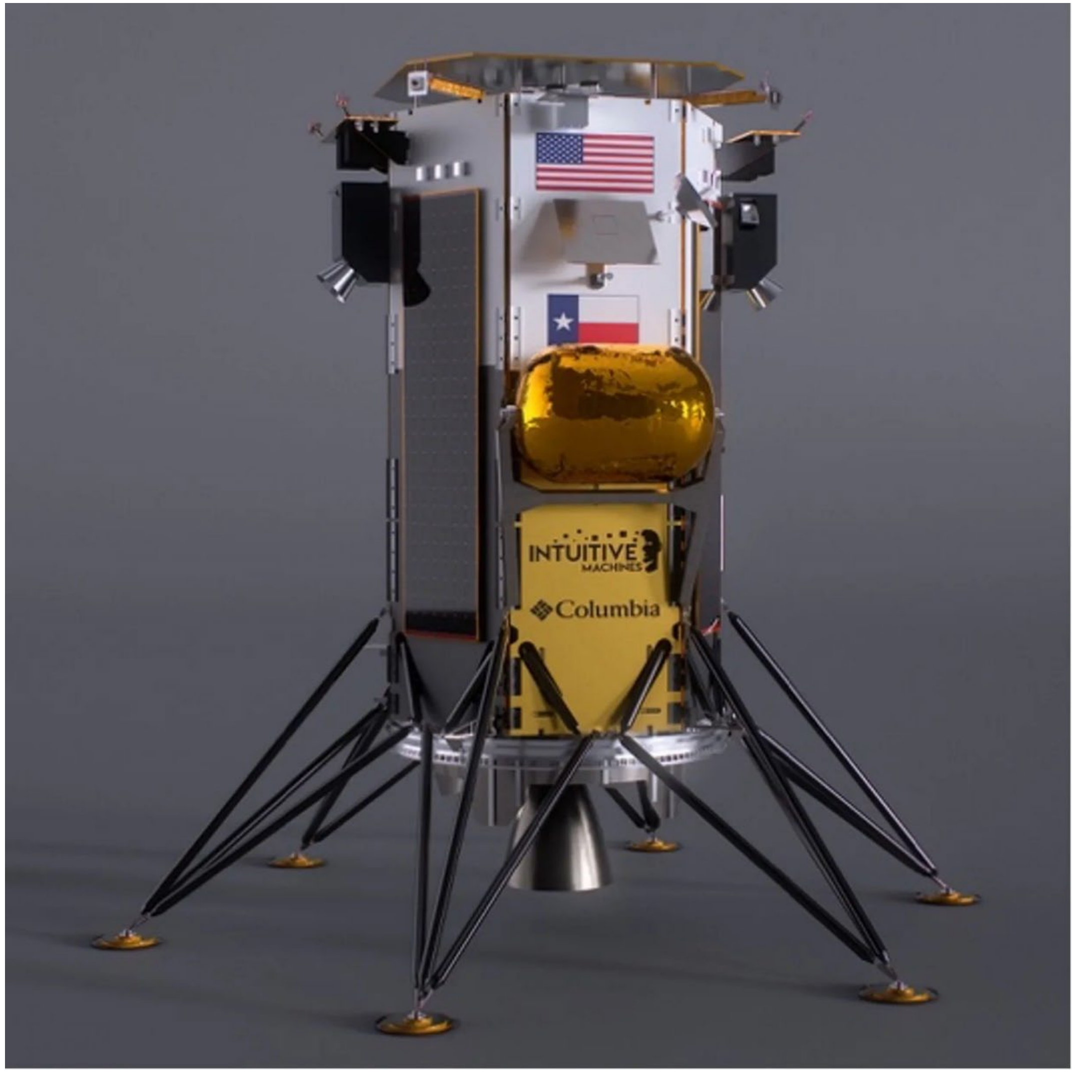
- Currently scheduled to launch on Jan 12th, 2024
  - Landing no earlier than late January
- Single central main engine (similar to Apollo)
- Engine thrust throttleable up to 3100N (about 10x smaller than Apollo)
- Liquid Oxygen / Liquid Methane propellants (Apollo used Aerozine 50 and NTO)
- Will be carrying SCALPSS instrument to visualize crater formation

Provides first opportunity to validate Apollo calibrated Loci/CHEM-DIGGEM model with flight data



Intuitive Machines Nova-C Descent Simulation

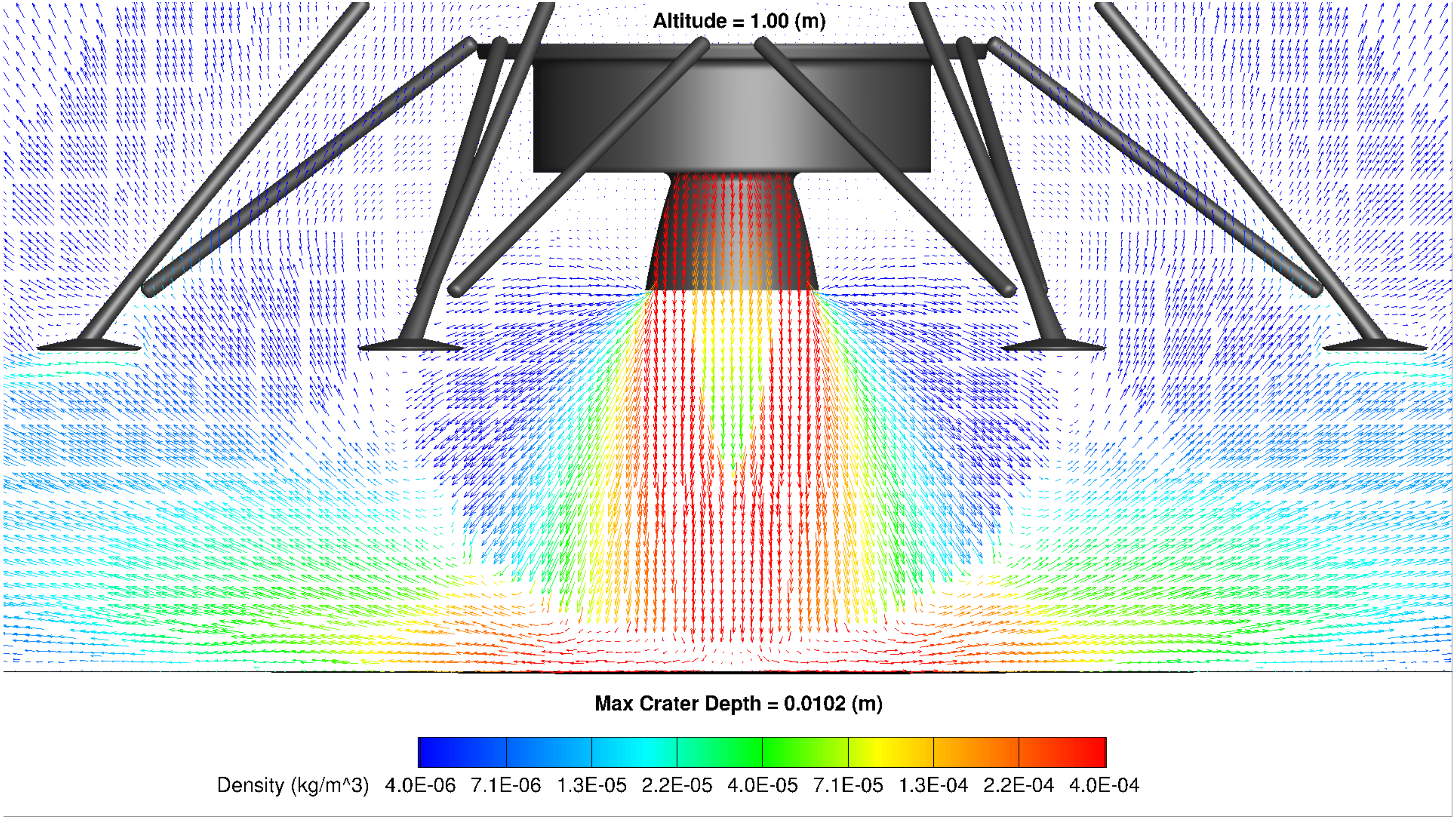
- Final 36 m of descent
- Thrust and vehicle position with time matched to nominal descent trajectory
- 120 Million cell mesh
- 23,000 timesteps
- ~6 days on 4000 processors



Intuitive Machines Nova-C Preflight Prediction

Intuitive Machines Nova-C Preflight Prediction

By time vehicle reaches 1m altitude only 1 cm of regolith has been eroded



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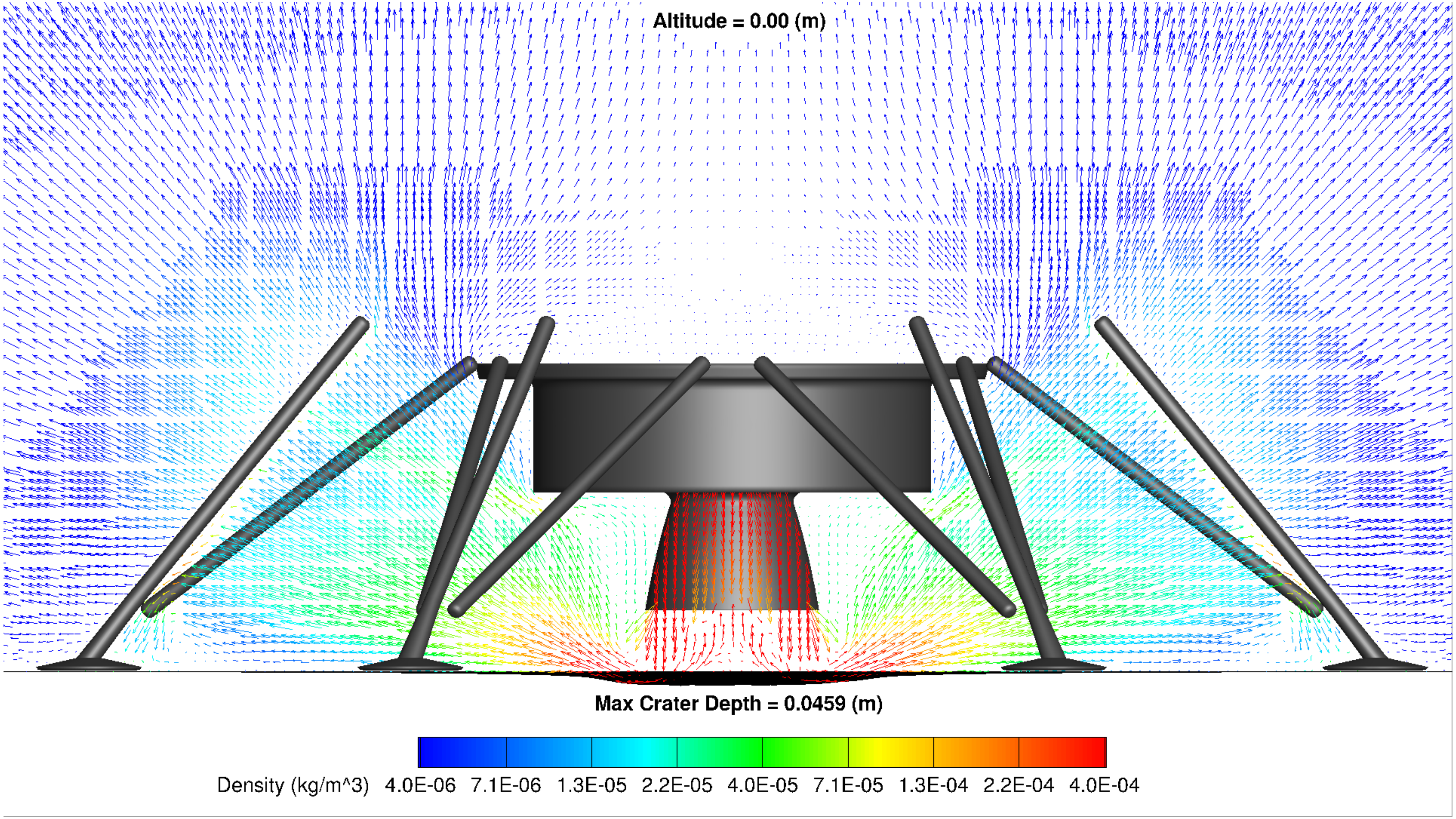
Intuitive Machines Nova-C Preflight Prediction

At touchdown, over 4.5 cm of regolith have been eroded and plume flow is altered by crater shape



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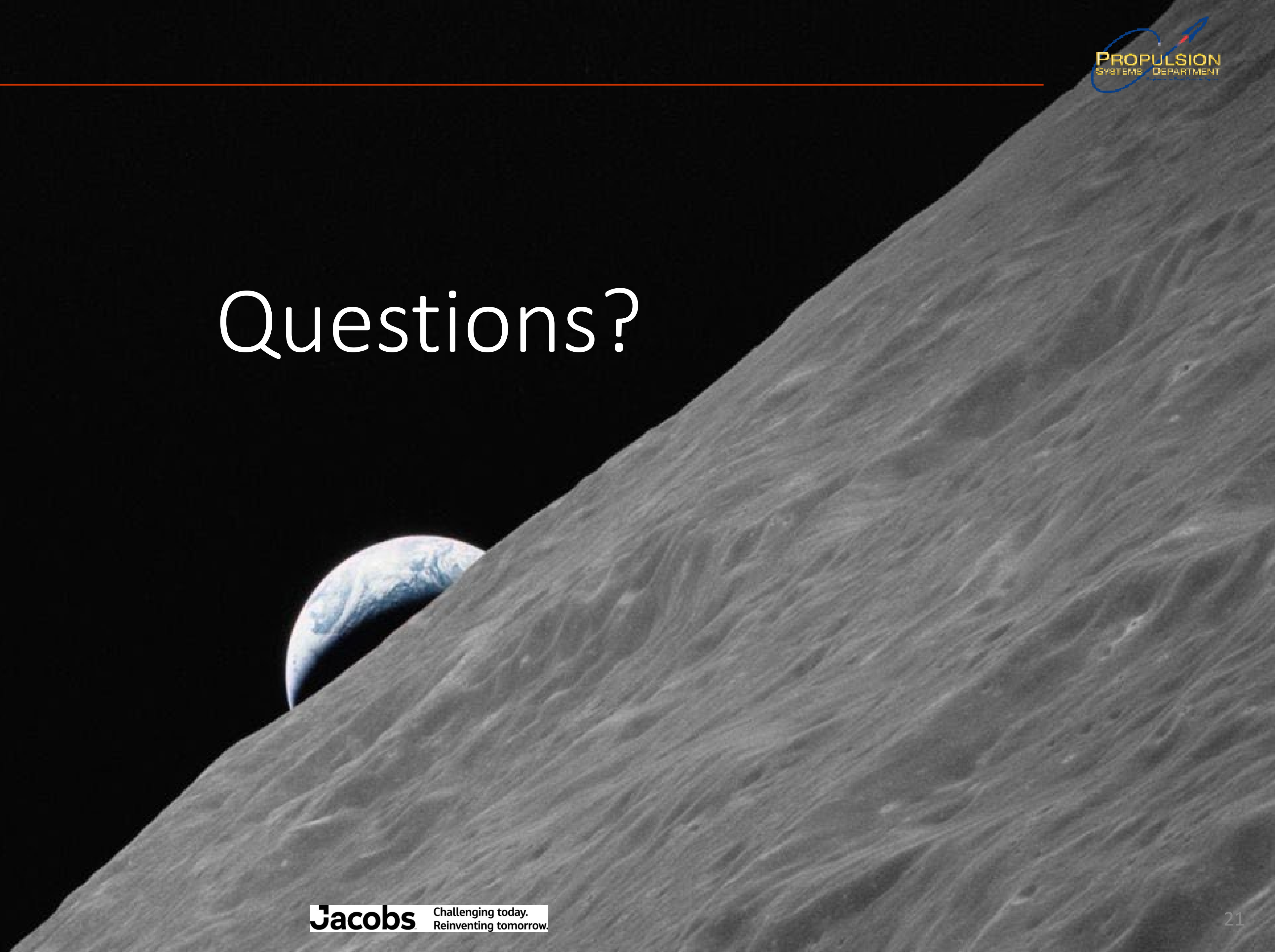
Future and Ongoing Work

- Validate and recalibrate if necessary, using SCALPSS data from Nova-C landing

- Preflight predictions for other CLPS and HLS landers
  - Informs design decisions about instrument placement, PSI mitigation measures, ConOps, GN&C profiles, etc.

- Evaluate additional metrics for other PSI instrumentation
  - Debris impacts, ejecta trajectories, dust/obscuration onset

- Integration of DIGGEM with other tools with additional capabilities
  - SPM (static porous media) for diffusion driven flow and fluidization prediction



Questions?

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