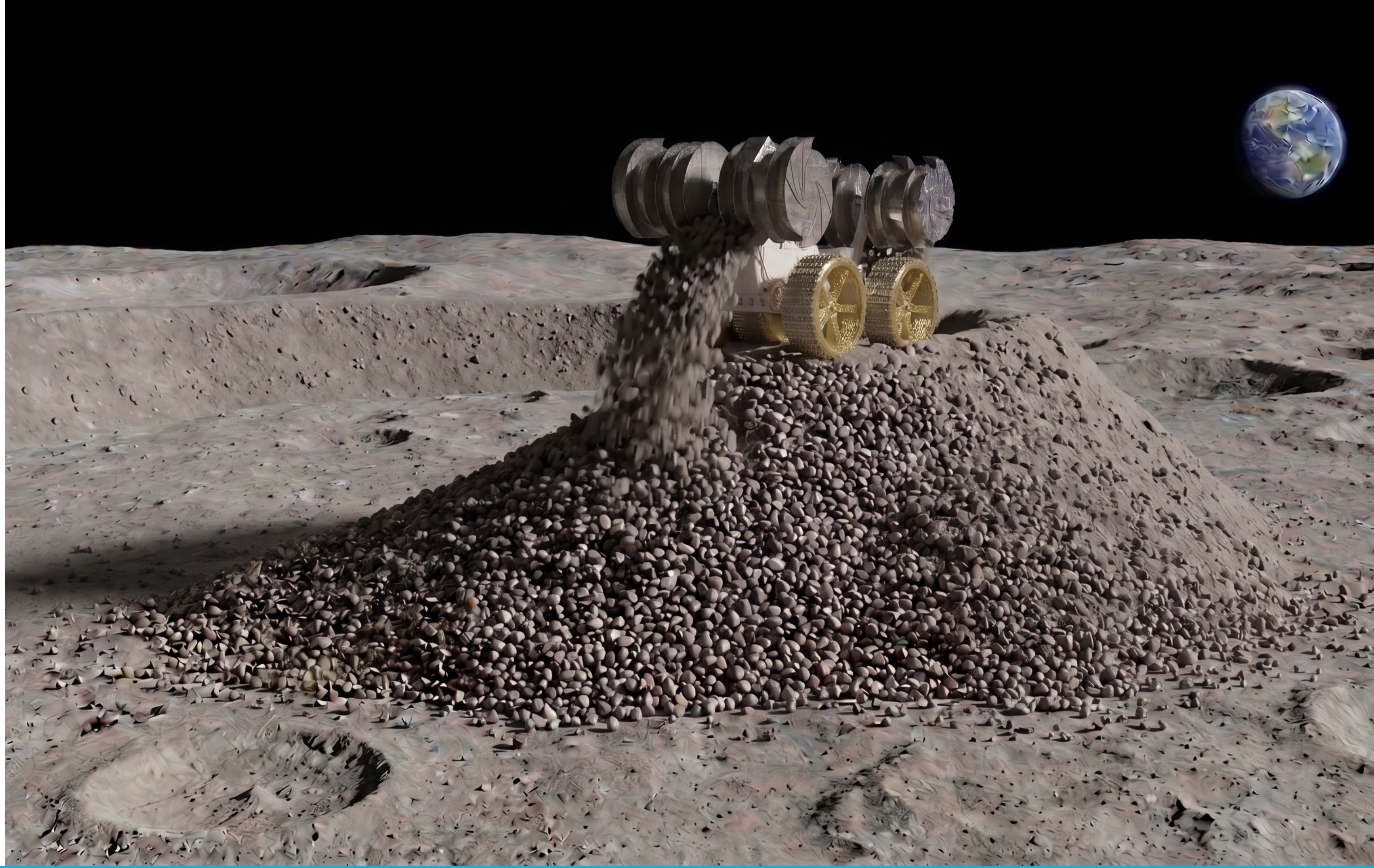
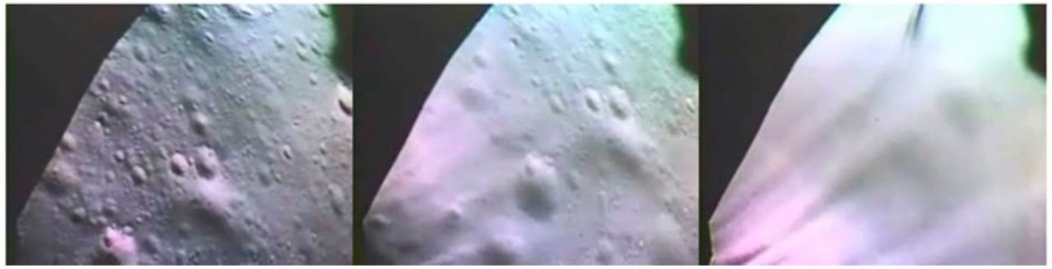


Evaluation of Untreated Regolith Berm Geometries for Lunar Ejecta Mitigation

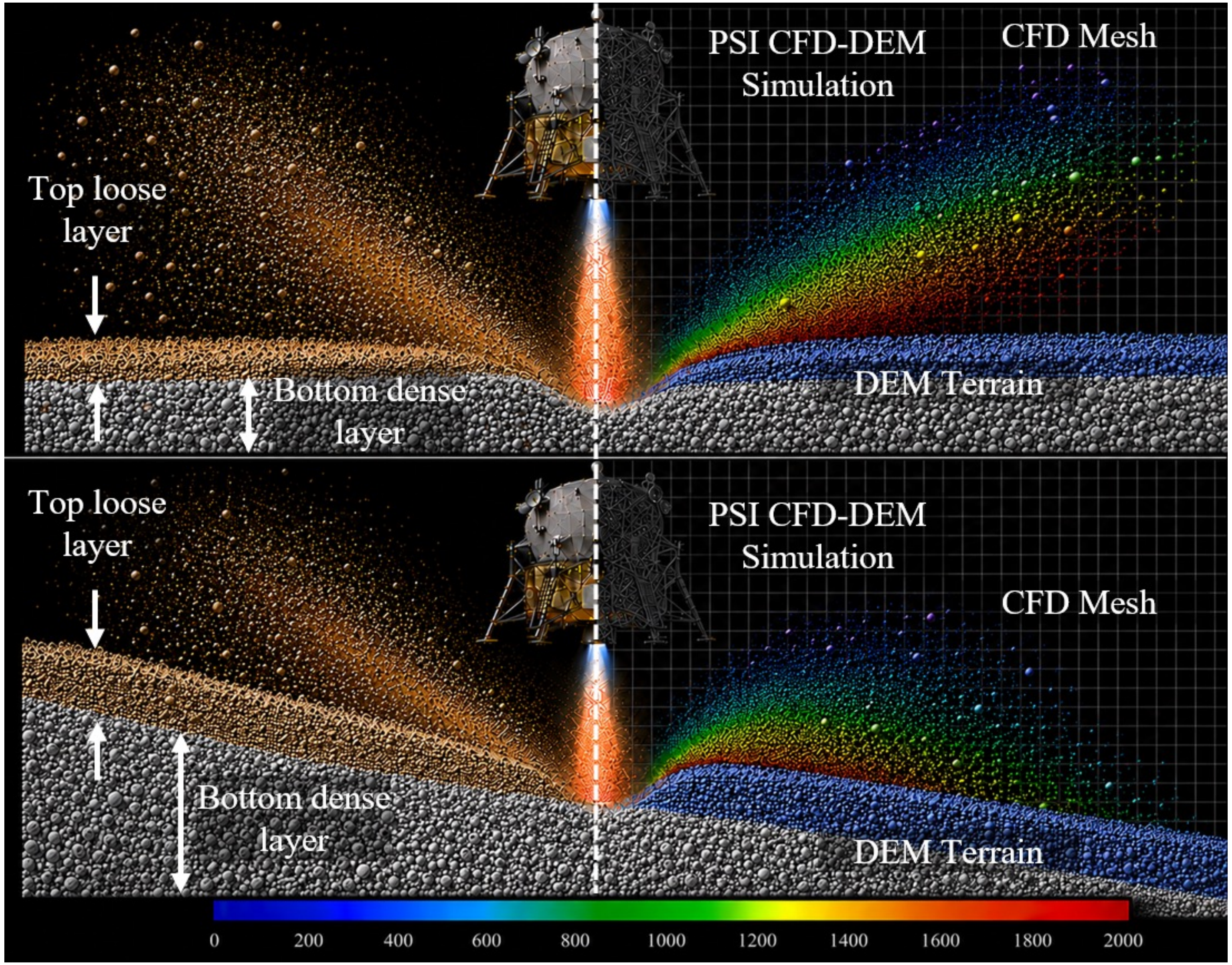
Space Resources Round Table - 2026
Zoheir Khademian, PhD – zkhademian@outward.tech
Blueshift, LLC dba Outward Technologies

Background



Dust obscuration during Apollo 16 Lunar landing (Metzger, 2010)

- Plume-Surface Interaction (PSI) causing high-velocity ejecta that might damage surrounding surface infrastructure.
- Berm design: landing pad radius, berm geometry, and material.
- Lunar Landing Pad Design Tool (LLPDT) uses Discrete Element Method (DEM) to simulate complex regolith physics and berm structural stability. *A tool for hardware designers, site planners, lander companies.*



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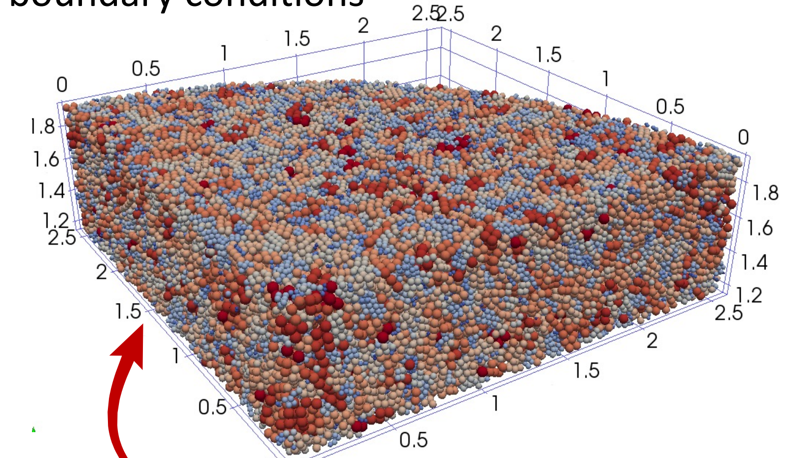
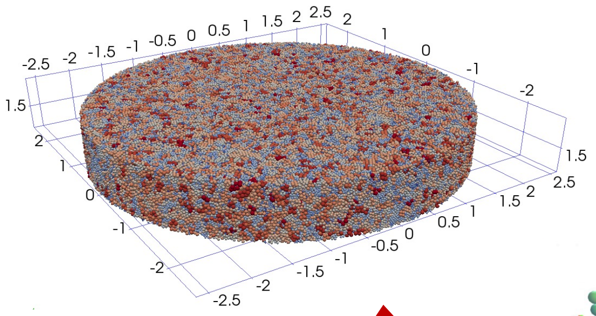
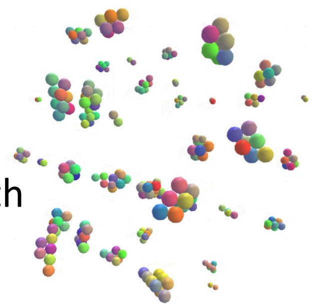
Methodology: Discrete Element Method (DEM)

Landing pad with symmetry boundary conditions

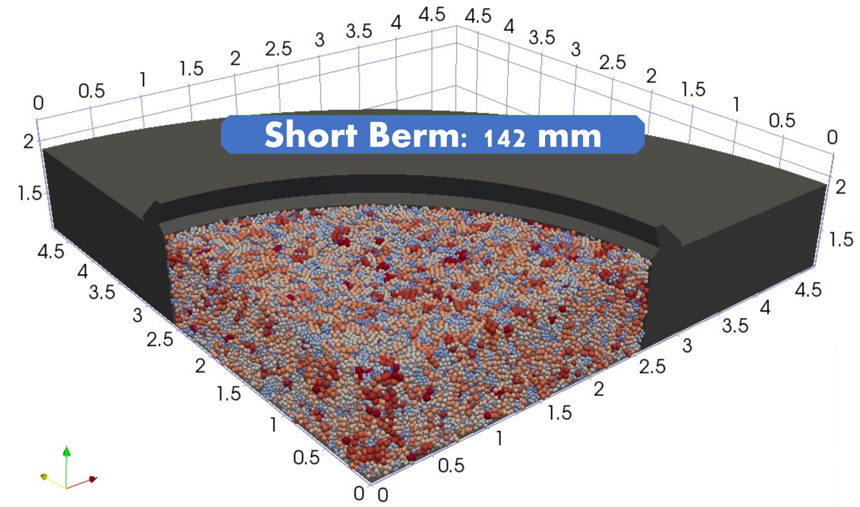


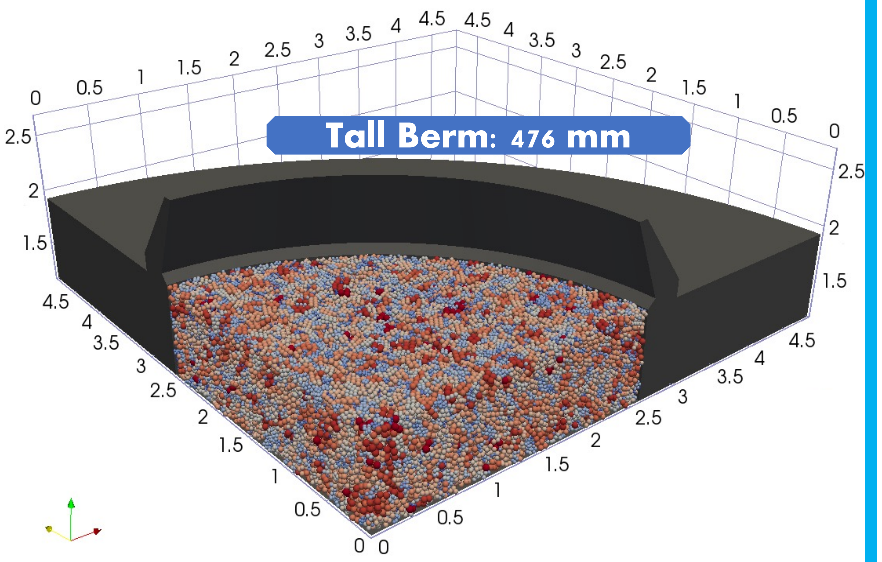
Regolith bed with bulk density 1400-2100 kg/m3



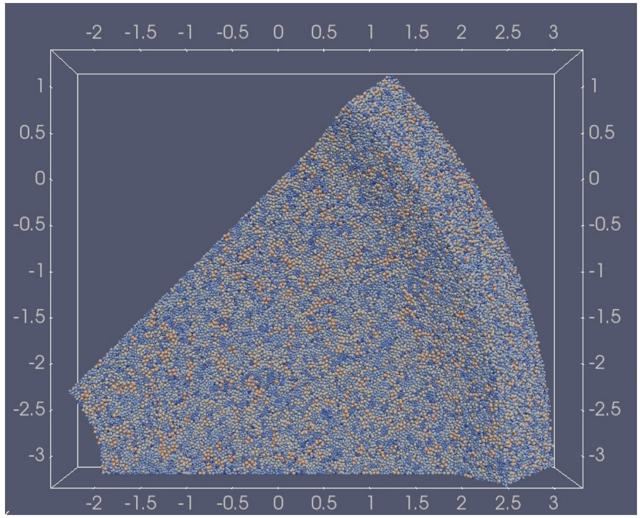


Apollo 16 sample regolith characteristics

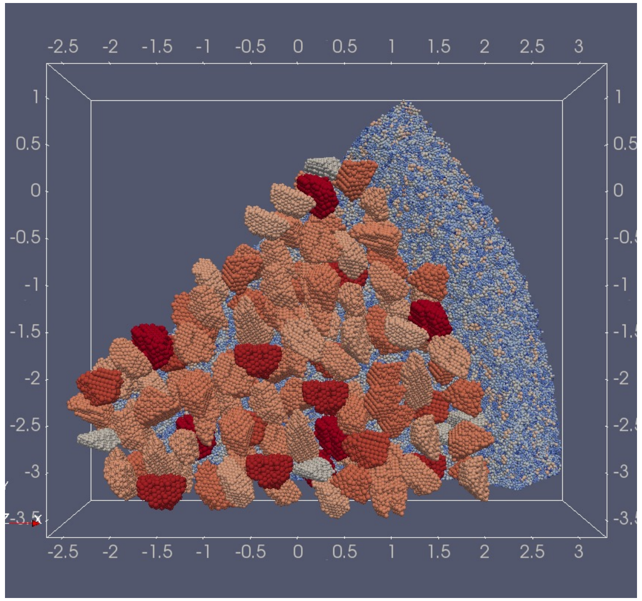




Ballast wall structures



Landing pad with regolith berm



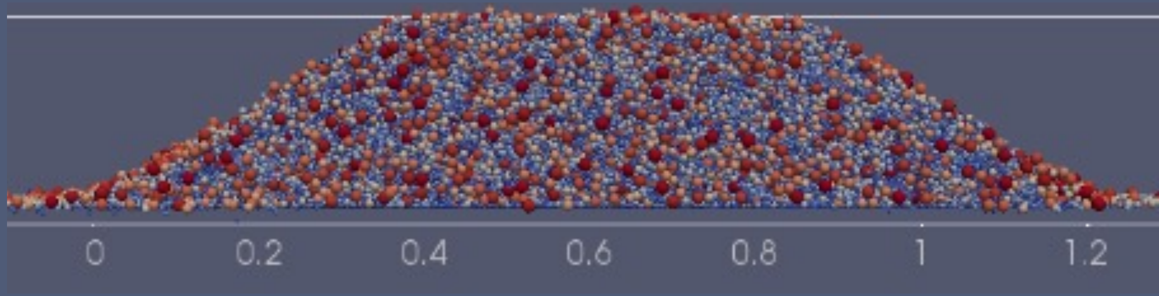
Landing pad with surface boulders and regolith berm

Methodology: Regolith Berm Design

- A trapezoidal cross-section with a flat top, formed by incremental deposition of regolith while traversing over the berm
- More mass-efficient for taller requirements, for a 2.5 m height, walls require less mass than ramp berms for lengths exceeding 9 m.

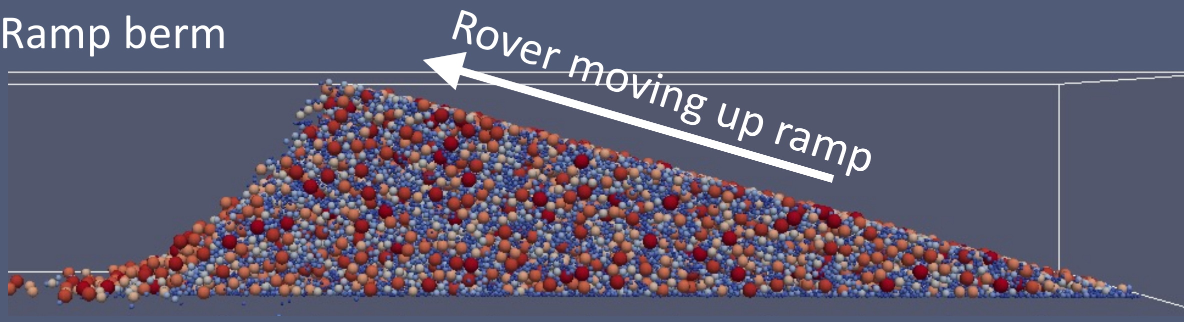
Wall berm

Rover moving along the berm in the in-plane direction



- A triangular cross section, formed by repeating parallel deposition operations,
- Facilitate rover access for maintenance,
- Mass-efficient for shorter structures, requires less mass than wall berms for heights under 1.5 m and lengths beyond 33 m.

Ramp berm



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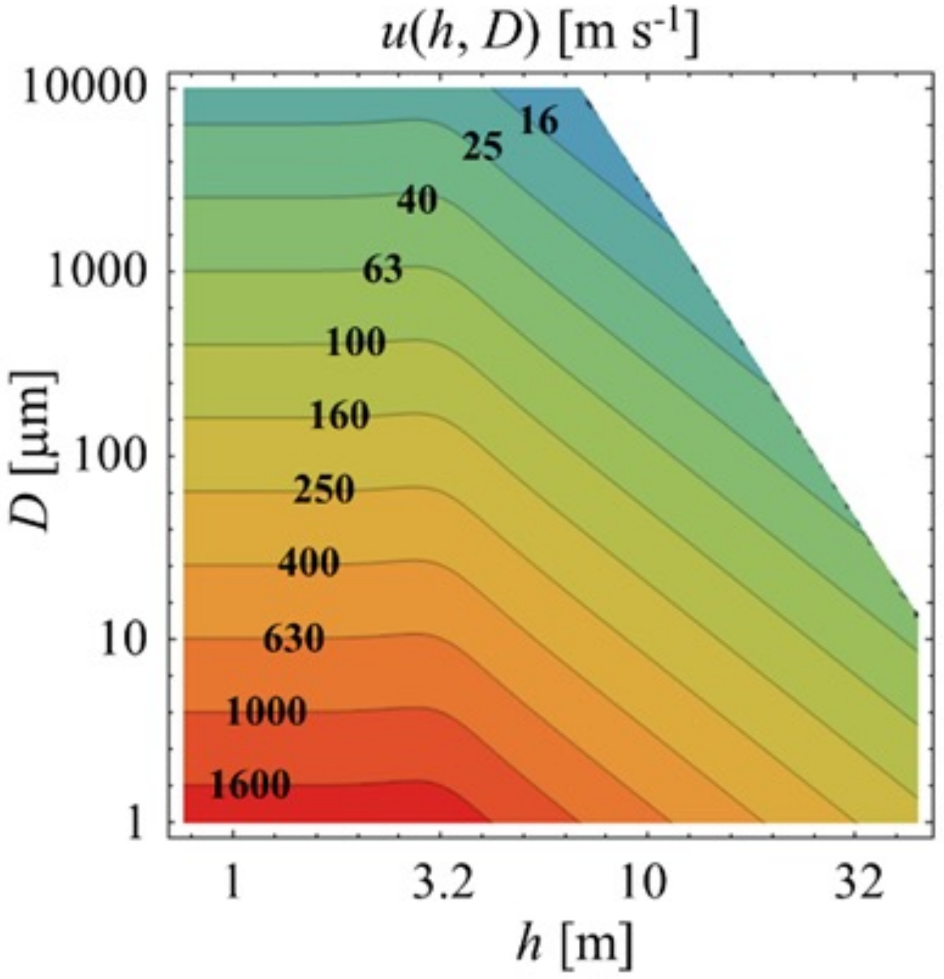
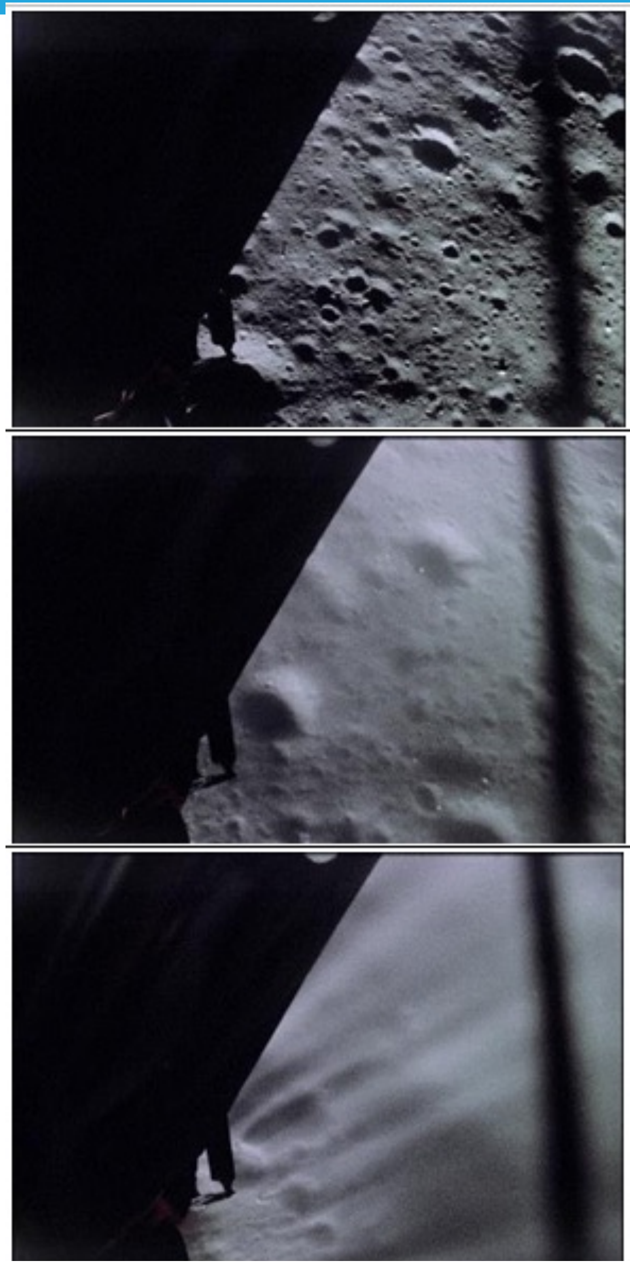
Methodology: Computational Optimization and Scaling

Ejecta concentration: 10^8 to 10^{15} particles/m³ based on Apollo mission video photogrammetry (Immer et al., 2021).

Ejection angle: <3° from initial photogrammetric studies of Apollo missions.

Velocity Field Derivation: A function of particle radius and elevation from Apollo Lunar Module CFD simulations (Lane et al., 2010).

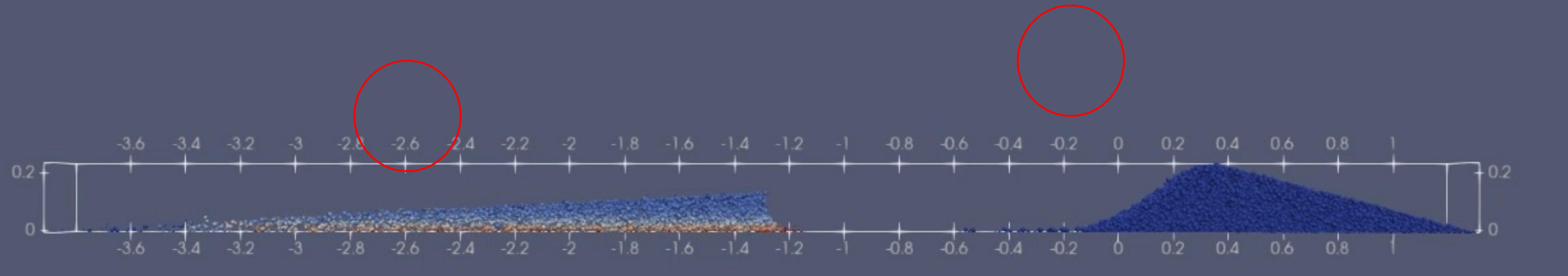




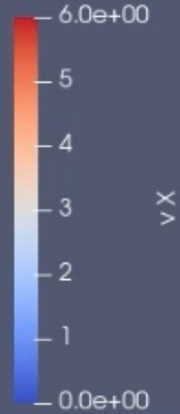
(Immer et al., 2021)

The Challenge: Simulating trillions of individual particles is computationally prohibitive.
Mass Scaling Solution: Conserved the ejecta volume fraction.

Results: Apollo-scale Landers



- Smaller particles (faster) collide with larger (slower) changing the ejection angle
- Berm blocks most of ejecta upon impact but redirects some to higher angles



Results: Damage Estimation

Brittle Targets

- **Primary Damage Metrics:** penetration depth and spall diameter.
- **Geometric Representation:** conical volume of the spallation zone.
- **Key Estimation Factors:**
  - **Target Properties:** Fracture toughness, elastic properties, and material density.
  - **Impact Dynamics:** Ejecta size, ejecta density, impact velocity, and incident angle.

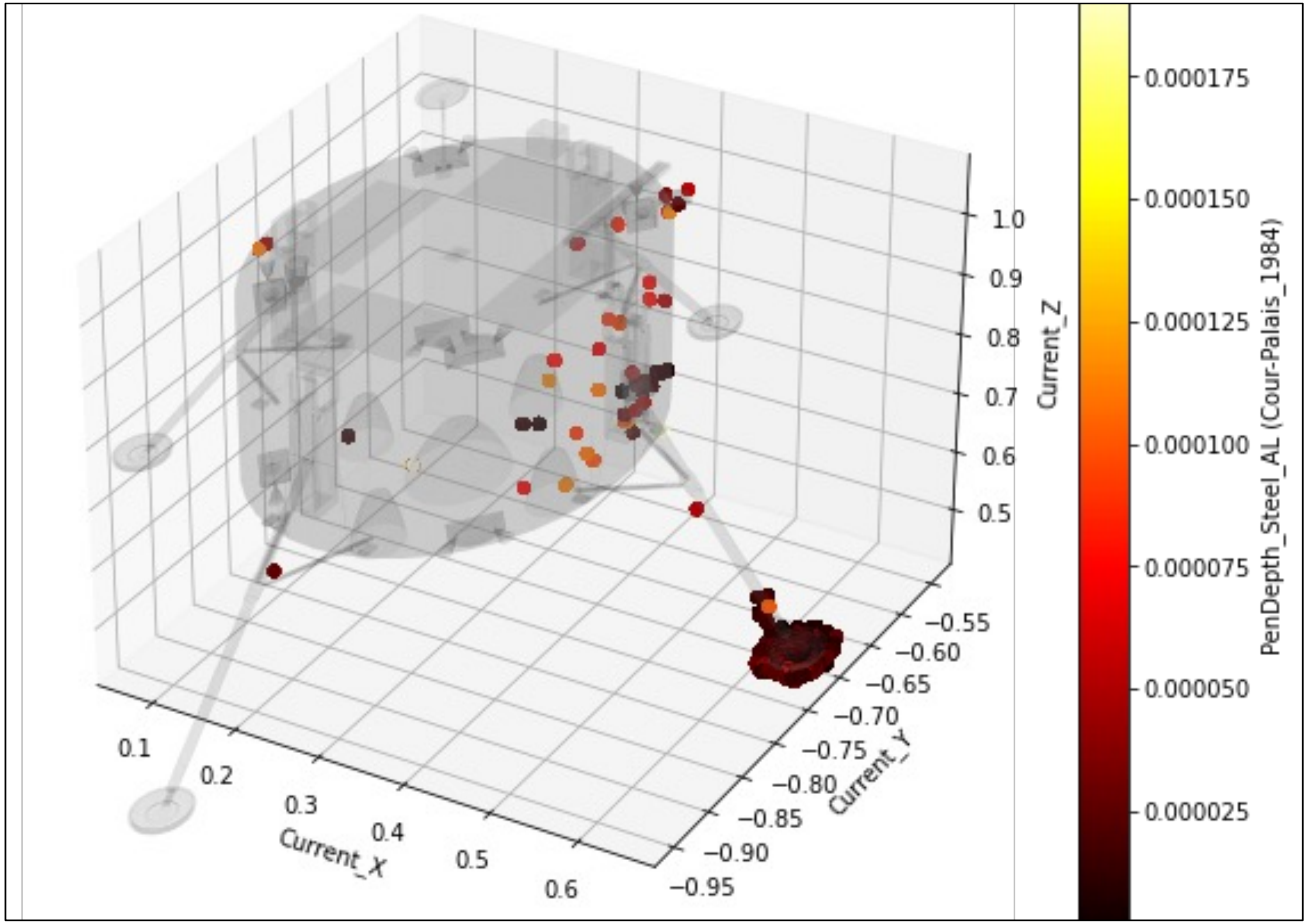
Ductile Materials

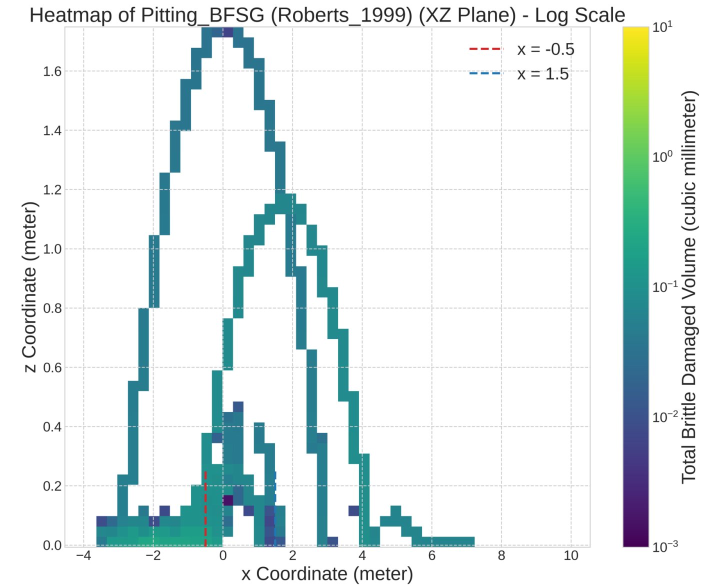
- **Primary Damage Metrics:** plastic deformation and impact radius
- **Geometric Representation:** penetration depth or deformed volume
- **Key Estimation Factors:**
  - **Target Properties:** Ultimate tensile strength, hardness indices, elastic properties, and material density.
  - **Impact Dynamics:** Ejecta size, ejecta density, impact velocity

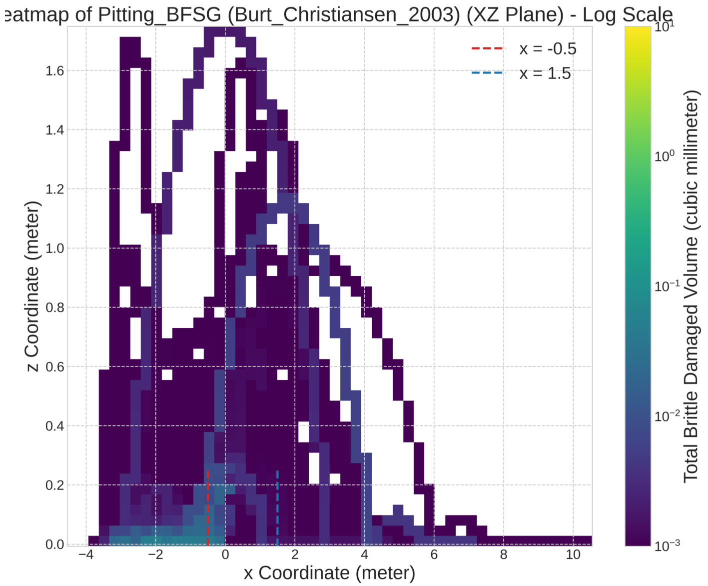
	Equations	References
Fused silica glass	$P = 0.96\, d_p^{1.26} V_n^{0.67}$ $D_{sp} = 9.83\, d_p^{1.03} V_n^{0.57}$ P penetration depth; D_{sp} spall diameter in cm; V in km/s;	(Jiyun et al., 2010)
	$P = 0.266\, \rho_p^{0.595} d_p^{1.06} V^{0.995} (\cos\theta)^{0.496}$ $D_{sp} = 9.656\, \rho_p^{0.373} d_p^{1.183} V^{0.915} (\cos\theta)^{0.545}$ D in cm; V in km/s and Rho in g/cm3	(Burt & Christiansen, 2003)
	$P = C\, \rho_p^{0.519} V_n^{0.67}$	(Cour-Palais, 1987)
satellite mylar surface and solar panels	$P = K\, m^{0.352} \rho_T^{1.667} V_n^{0.875}$ K: constant depending on target material	(Lai et al., 2012; Tribble, 2020)
	$P = 0.7658\, d_p^{0.056} \left(\rho_p/\rho_T\right)^{0.476} (\sigma_{Al}/\sigma_T)^{0.134} V_n^{0.806}$	(Lai et al., 2012; McDonnell & Sullivan, 1991)
	$D_{sp} = \left(\frac{0.375\, d_p f}{E^*}\right)^{0.334}$ $if\ KIc < \left(\frac{2E^* f}{C\, d_p}\right)^{0.5}$ $1/E^* = \frac{1-\nu_P^2}{E_p} + \frac{1-\nu_T^2}{E_T}$ KIc: Glass fracture toughness; f force applied by the sphere on glass For a glass substrate with $\nu_P = \nu_T = 0.22$ indented with a sphere of the same glass, C = 3131	(Oh & Finnie, 1967; S. G. Roberts et al., 1999; Warren, 1995)
Metallic targets	$t = K\, m^{0.352} V_n^{0.875} \rho_{\square}^{0.1667}$ t is the plate thickness to prevent rupture from ballistic penetration.	(Fish & Summers, 1964; Hayashida & Robinson, 1991)
	The maximum pulse force over the contact time $f_{Cmax} = 1.92\, \rho^{3/5} (\delta_1 + \delta_2)^{-2/5} R^2 V^{6/5}$ $P_{max} = \left(9\, f_{Cmax}^2 / (16\, R\, (\delta_P + \delta_T)^2)\right)^{1/3}$ and δ is $(1-\nu^2)/(\pi E)$ $P_Y = f > \frac{\pi R^2 \delta^2 A_y^3 \sigma_y^3}{6}$ $P_{plastic} = P_{max}(1 - \frac{f_{Cmax}}{4/3E\sqrt{R}\, P_{max}^{3/2}})$ $R_{plastic} = \frac{f_{Cmax}^2}{\left(\frac{4}{3E}\right)^2 (P_{max} - P_{plastic})^3}$ $a_{plastic} = \sqrt{R_{plastic} P_{plastic}}$	(Brake, 2015; Vu-Quoc et al., 2000)
Aluminum target.	$t = \frac{d(\rho_p/\rho_T)^{0.159}}{2.06\left(\frac{2.68\sigma_{Tult}}{\rho_p V_n^2}\right)^{0.236}}$; σ_{Tult} t lb/in2; d and t in inch; density in lb/in3;	Payne, Gault, Wedekind, et al
	$P = 1.38\, d^{1.1} (BH)^{-0.25} \rho_p^{0.5} \rho_t^{-0.167} V^{0.67}$ In cm, g/cm3, and km/s. BH: Brinnell Hardness for target. For ballistic limit, t=1.8 P and for spallation limit t=3P	(Hayashida & Robinson, 1991)
	$P = 5.24\, d^{1.056} (BH)^{-0.25} (\rho_p/\rho_T)^{0.5} (V_n/C)^{0.67}$ if ρ_p/ρ_T<1.5 $P = 5.24\, d^{1.056} (BH)^{-0.25} (\rho_p/\rho_T)^{0.67} (V_n/C)^{0.67}$ if $\rho_p/\rho_T \geq$1.5	(Christiansen, 1991; Cour-Palais et al., 1987)

Results: Damage Estimation

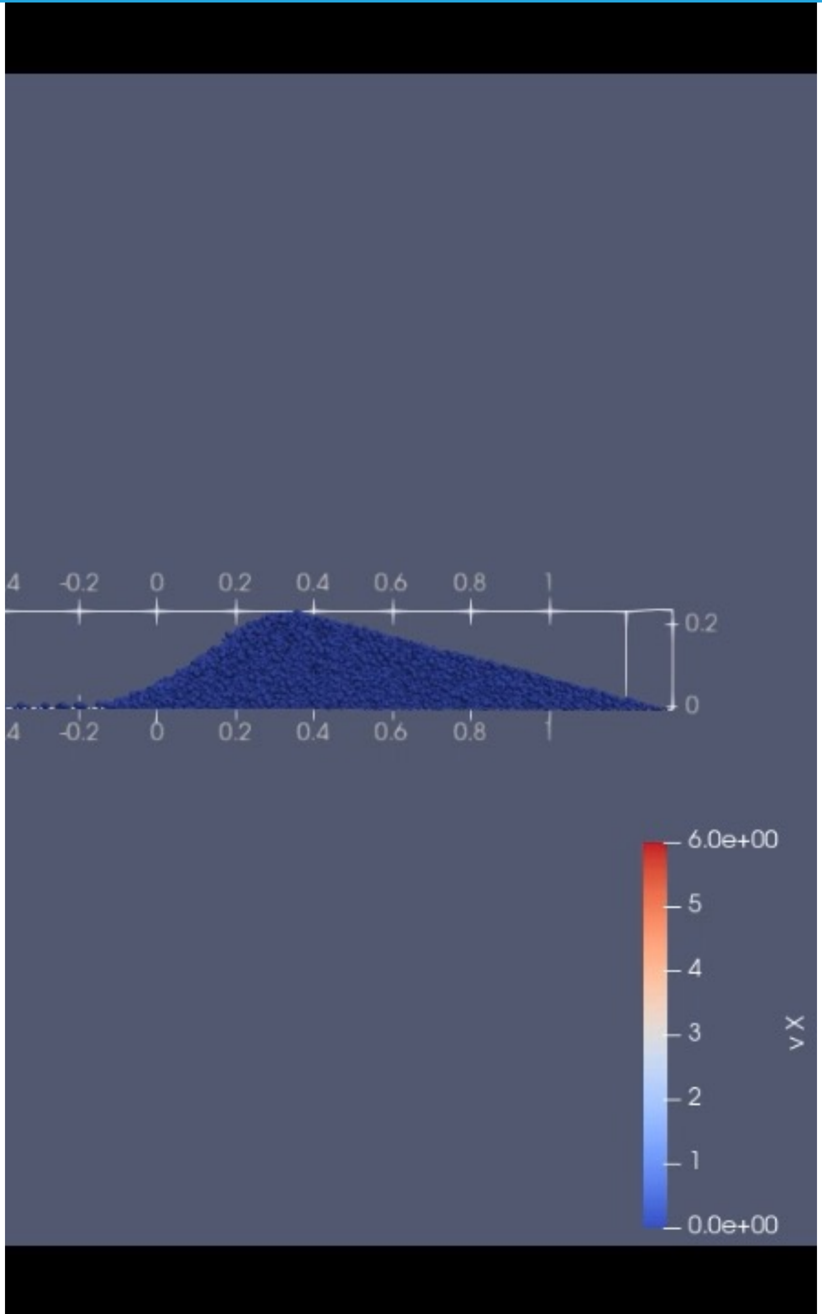
- Geometry specific damage: site specific and lander specific
- Heat maps: Generic tools evaluating damage within any distance from landing

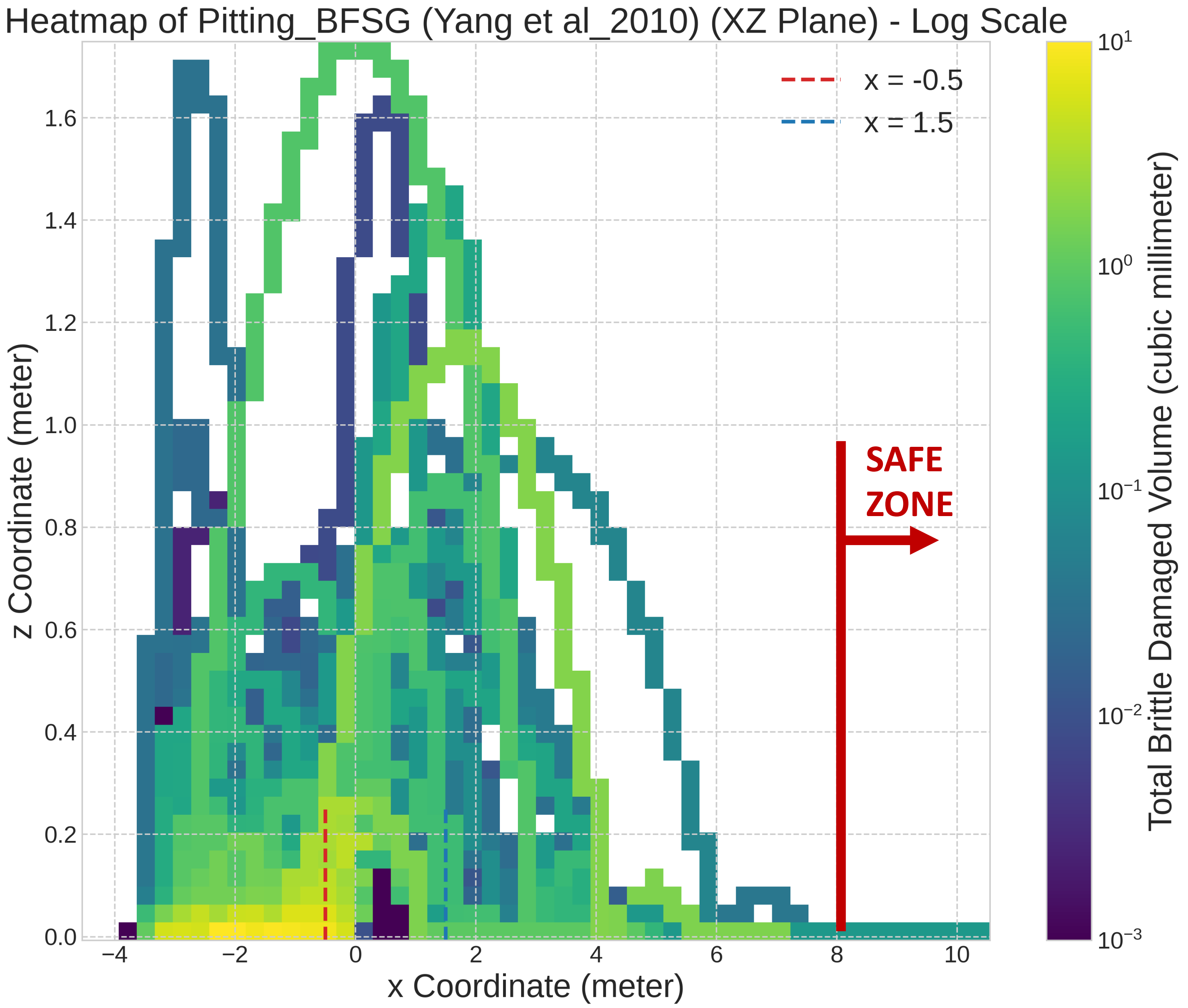






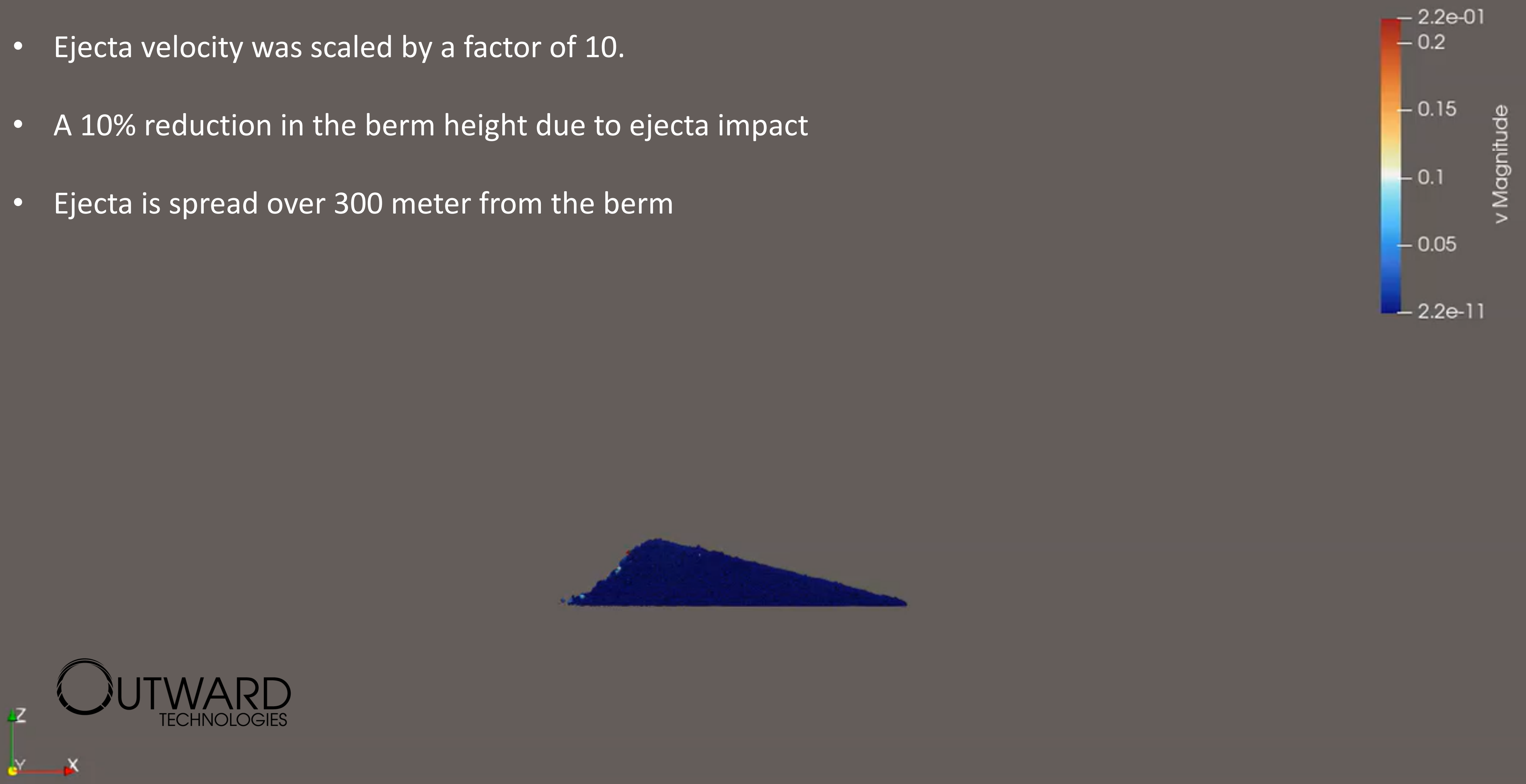
Results: Apollo-scale Landers





Results: Berm Performance – Ramp Berm

- Ejecta velocity was scaled by a factor of 10.
- A 10% reduction in the berm height due to ejecta impact
- Ejecta is spread over 300 meter from the berm

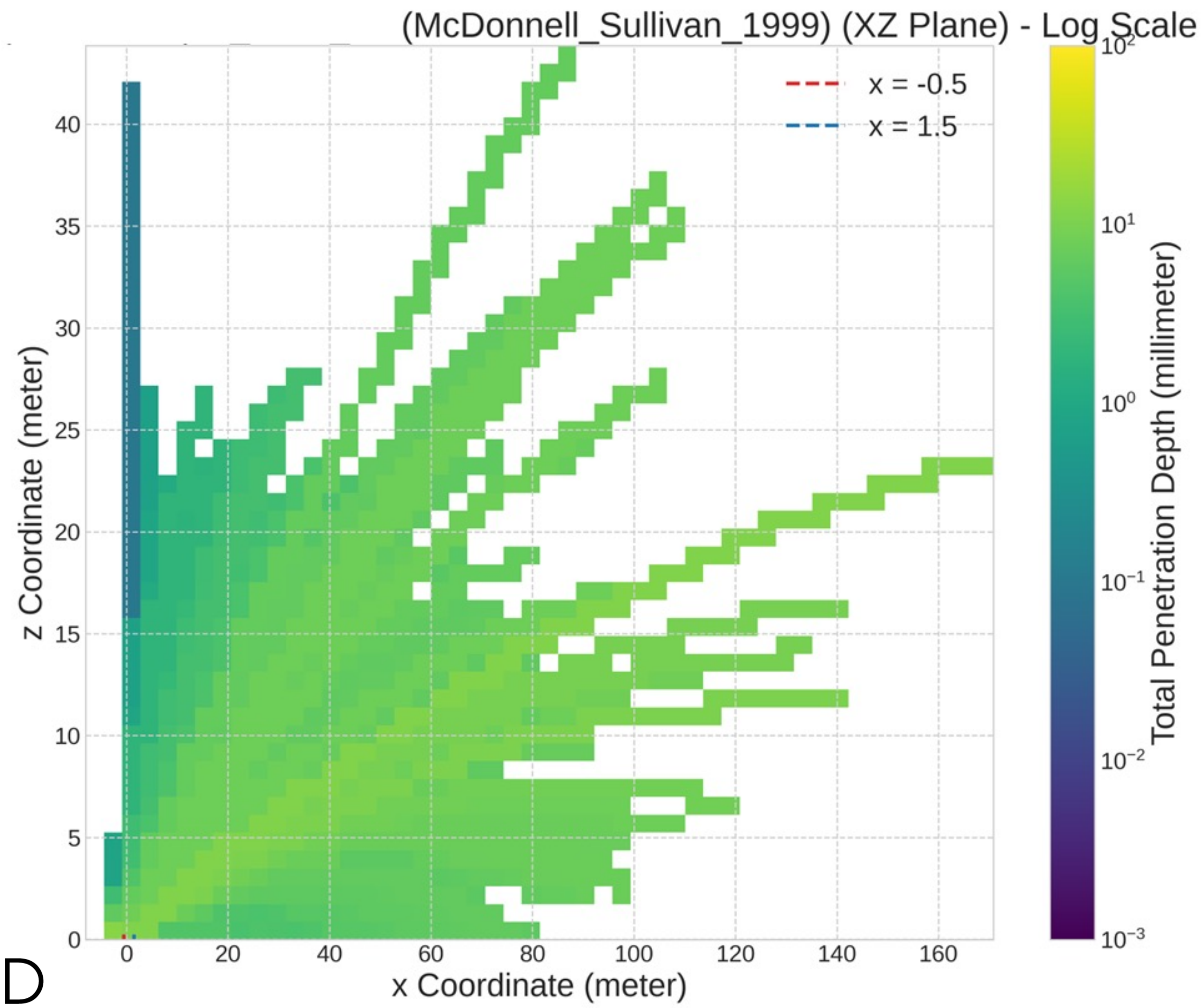


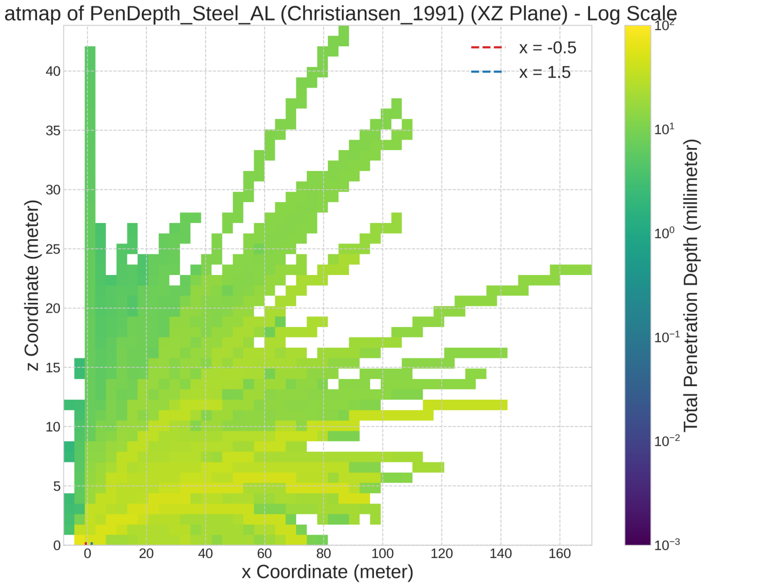
Results: Berm Performance – Wall Berm

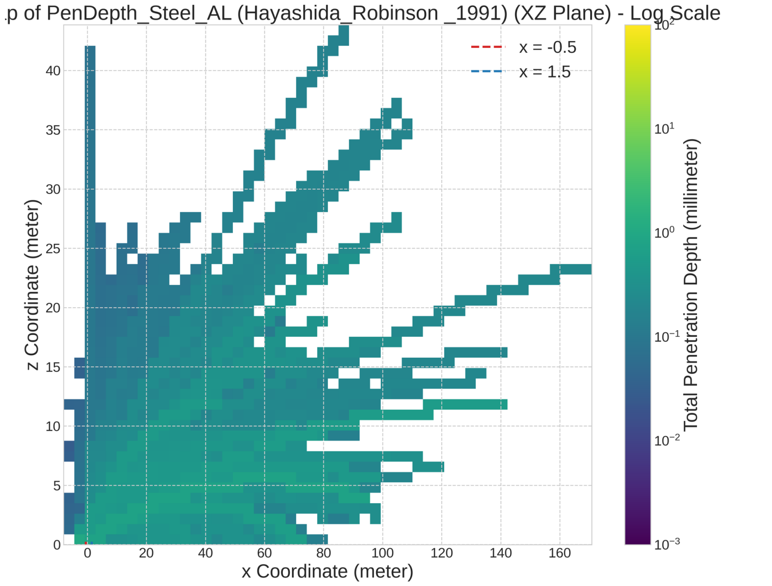
- Wall berm maintained its height after impact
- Active face angle reduced from 50° to 40.
- Ejecta is spread over 300 meter from the berm

Results: Damage Estimation

- Scaling ejecta velocity by a factor of 10 increased the radius of influence by a factor of 30.
- Damage intensity various across different estimation techniques







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Summary

- **Wall Berms:** Provide superior immediate shielding and feature smaller physical footprint.
- **Ramp Berms:** facilitate maintenance and access but require broader exclusion zones due to wider potential damage domains.

- **Phase II plans for LLPDT development:**
  - **Enhancing LLPDT fidelity:** Full CFDEM PSI simulations calibrated against lab experiments at Colorado School of Mines and available lunar landing data (DERT and SCALPSS)
  - **Digital twin of rover/excavator:** path planning, construction strategies, geotechnical sampling strategies
  - **Parametric studies:** off-nominal landing trajectories, compaction of berms, range of ejecta velocities -> leading to a surrogate model
  - **Open source LLPDT Software**
    - Real-time modeling tool for berm design and estimation of ejecta-induced structural damage

OUTWARD TECHNOLOGIES

A big thank you to our collaborators!

- Beverly Kemmerer, PhD – NASA Technical Monitor
- Nima Goudarzi, PhD – Project PI
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- Ryan Garvey, PhD – Project Manager
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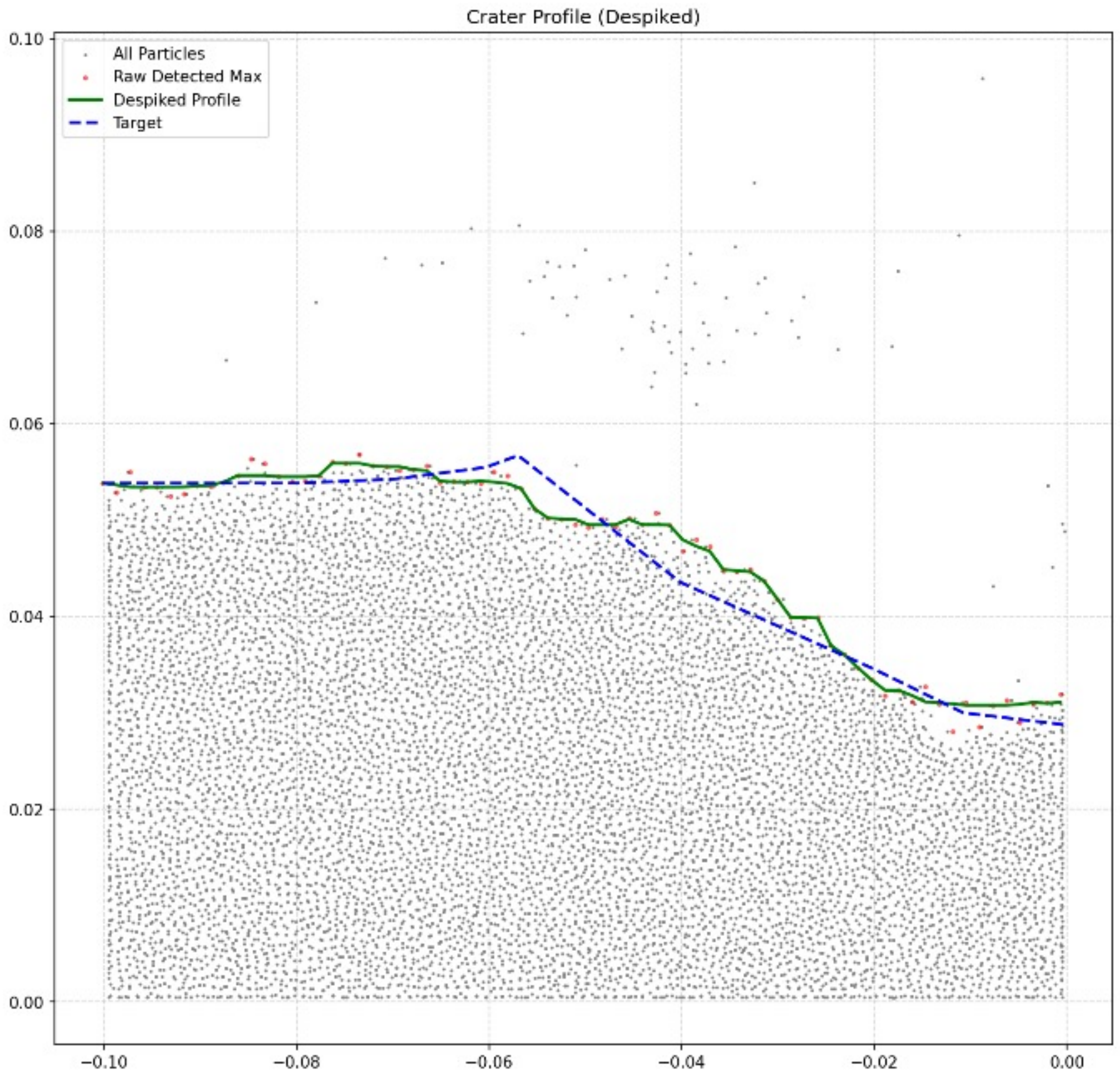
- Chris Dryer, PhD – Research Institution Lead
- Patrick Cooney – Research Assistant

Backup slides

CUI//SBIZ

Calibrate CFD-DEM Model-- Final Calibration Validation



Optimized Parameters

Params (.txt) Plots (.zip)

Parameter	Value
E_MOD	1.00799e+7
POISSON	0.448935
FRICTION	0.314494
RollingFRICTION	0.394637
RollingDAMPING	0.561351
CoeffRESTITUTION	0.791183

Calibration of CFDEM simulation parameters against the PFGT1 PSI experiment under near-lunar condition and nozzle mass flow rate of 0.32 gr/s.