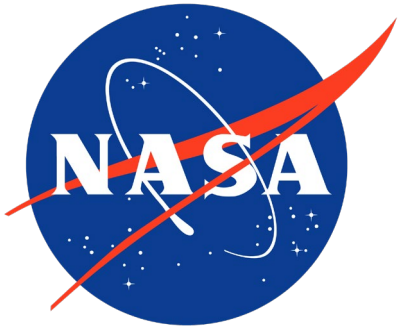


An overview of plume-surface interaction research

Wesley A. Chambers, Ph.D.

Deputy Principal Investigator, Plume-Surface Interaction Project

NASA Marshall Space Flight Center

University of Glasgow Seminar

24 August 2023

Outline

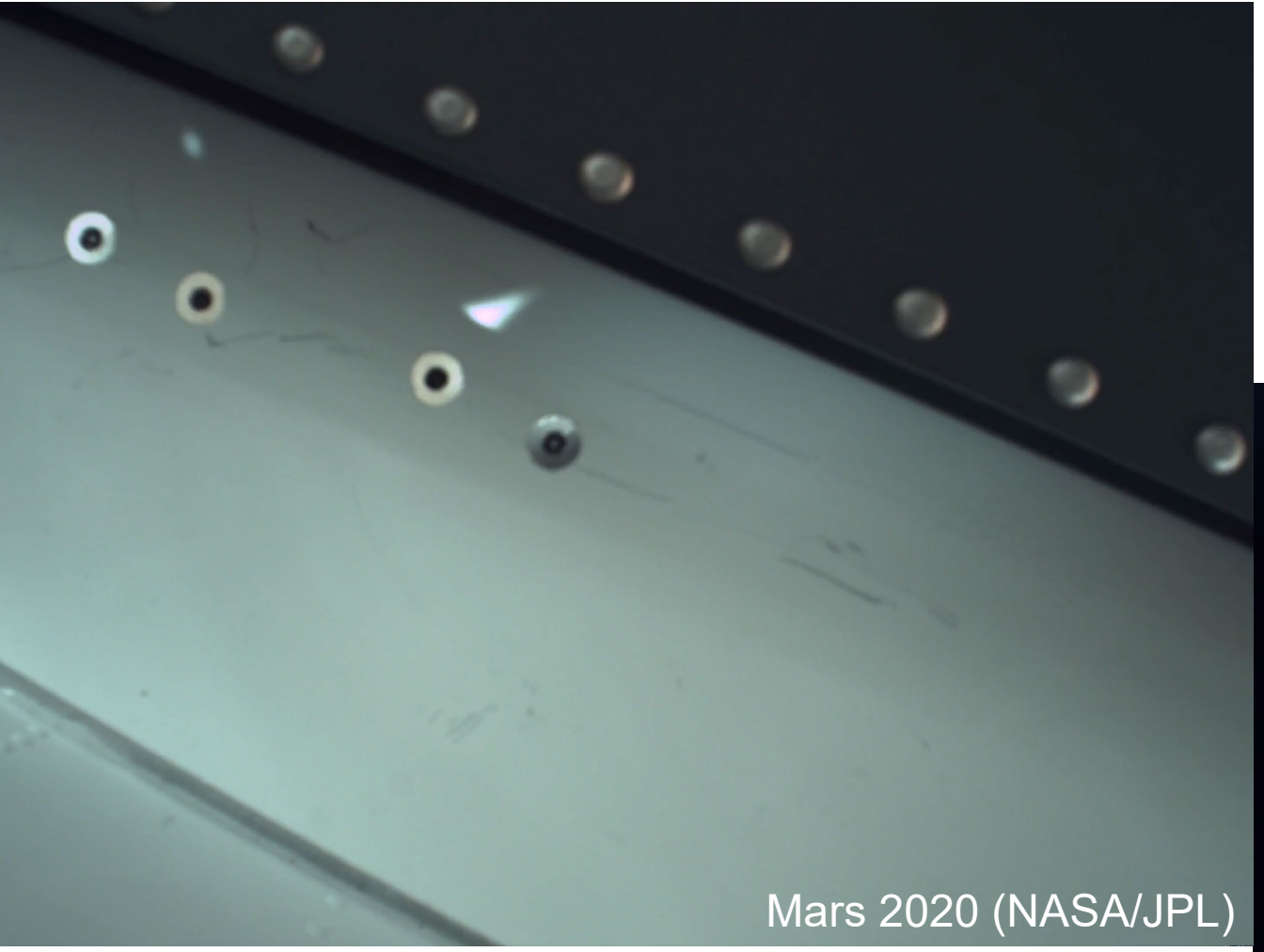
Introduction & Approach

Apollo and Viking

Research Since Apollo

Present and Future Efforts

Introduction & Approach
to Plume-Surface Interactions



Mars 2020 (NASA/JPL)

What are plume-surface interactions?



Apollo 11 (NASA)



NASA


SpaceX (CC BY-NC 2.0)

also plume-surface interactions (improved surface)


NASA/Goddard/University of Arizona

(intentional) plume-surface interactions



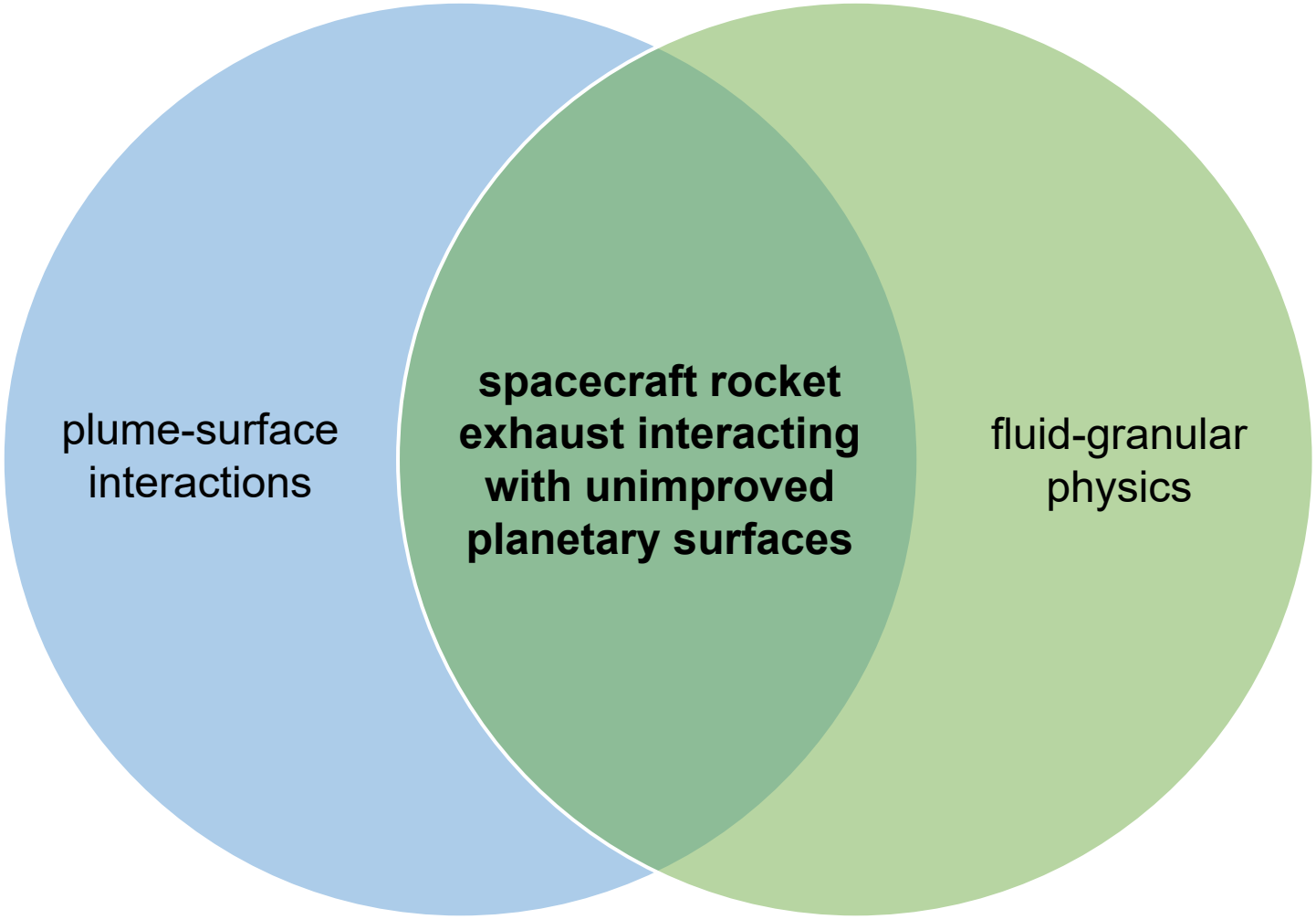
DOD/Army National Guard/Spc. Jovi Prevot

NASA/JPL-Caltech/ASU/MSSS

(rotor) plume-surface interactions


Wikimedia / Mark A. Wilson
Wikimedia/Mark A. Wilson/Public Domain

Which problem are we addressing?

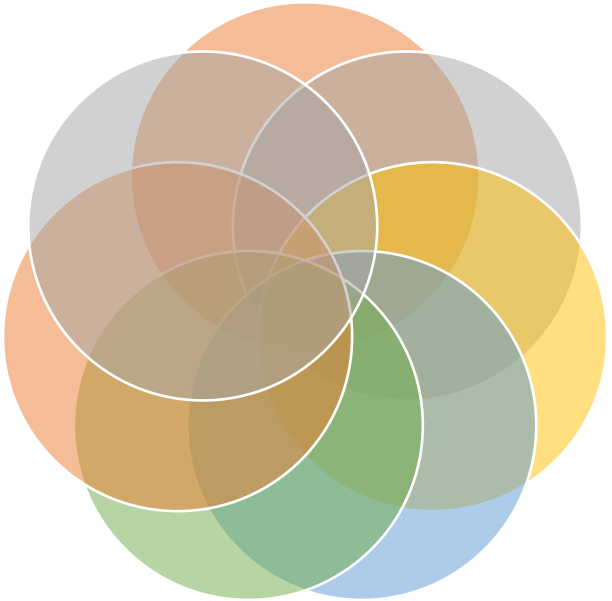


Study of plume-surface interactions is a complex, multi-discipline problem

Mission planning
& operations

Diagnostics &
instrumentation

Modeling &
simulation



Fluid physics

Granular
mechanics

Fluid-granular
physics

Facilities
Integrating diagnostics
Simulant handling &
characterization

Testing
capability

Planetary
science &
geology

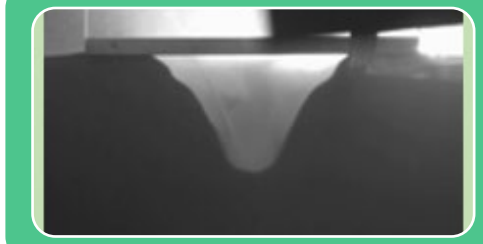
→ Simulant
selection

The “3-Legged Stool” Approach



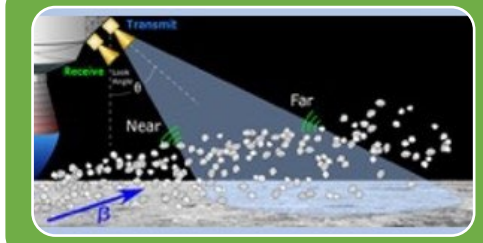
Modeling & Simulation

- Fills in testing and data gaps
- Large uncertainty, current tools need quantitative validation



Experimental Data

- Varying levels of fidelity
- Better control, instrumentation



Flight Data

- Ground truth
- Limited opportunities, data

What are we trying to achieve?

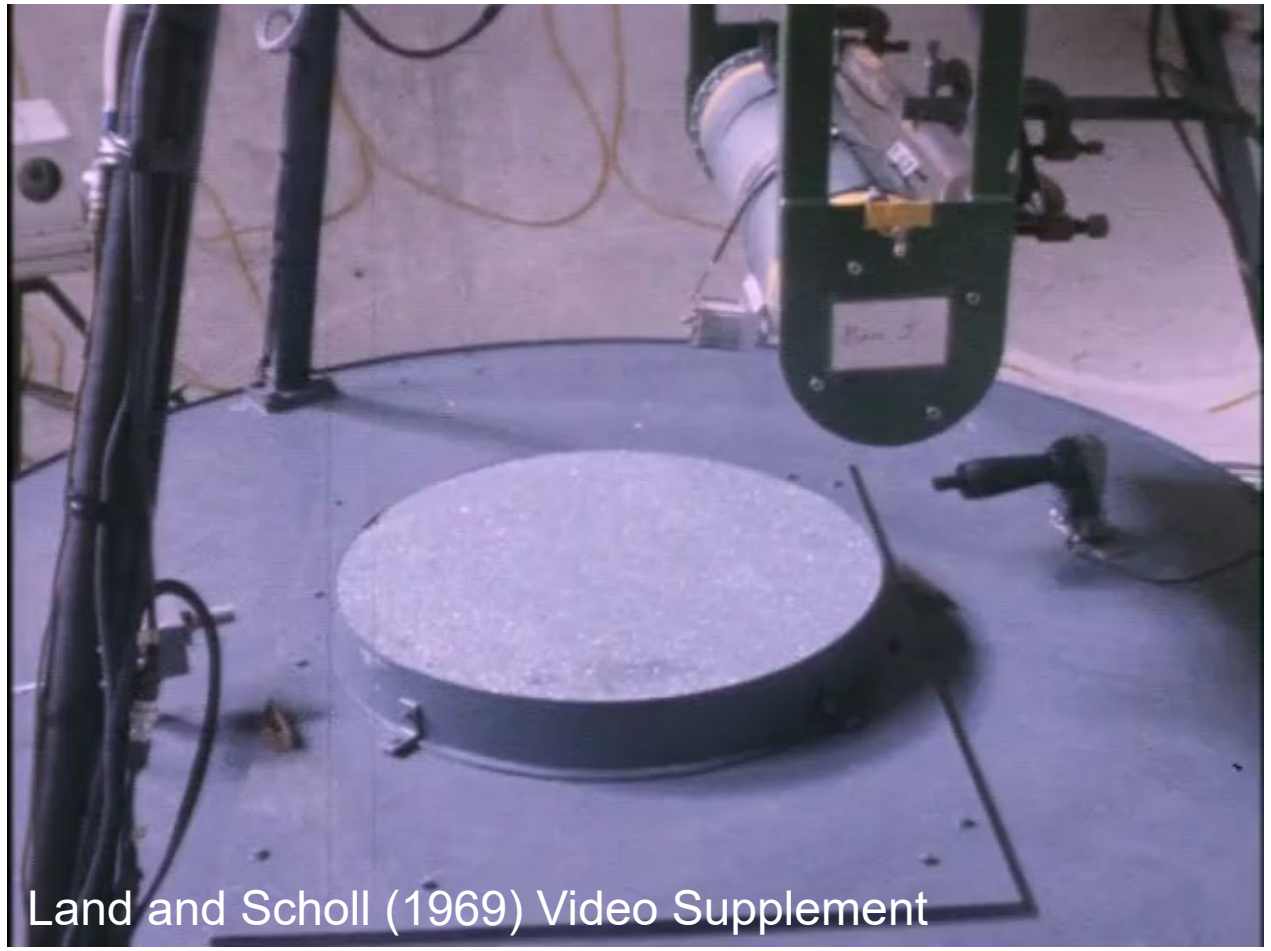
- An understanding of plume-surface interaction physics that enables predictive modeling so space missions can
  - Conduct successful near-surface operations
    - Spacecraft landing and ascent
    - Sampling operations
  - Mitigate surface alteration
    - Physical and chemical
  - Mitigate effects to surrounding assets
    - Impact, abrasion
    - Area of effect determined by vehicle, concept of operations, and environment of operations

Plume-Surface Interaction Research for Apollo and Viking

Apollo-Era PSI Research

Year	Modeling & Simulation	Test Data	Flight Data
1961		PSI test w/underexpanded jets, Lewis (now Glenn) Research Center[1]	**A decade of Apollo PSI risk reduction included modeling, multiple tests, precursor missions, and an *in situ* PSI experiment**
1962	Roberts' model on surface erosion[2]		
1963			
1964		First Technical Report written on PSI tests at the LaRC vacuum sphere[3]	
1965			
1966	Alexander report presents a theoretical treatment of in-atmosphere PSI test[5]	Surveyor Vernier engine PSI experiment in vacuum chamber[4]; Alexander report on in-atmosphere cold gas + hot fire testing[5]	Surveyor I mission lands
1967			Surveyor III, IV, V, and VI missions land; Surveyor V conducts in situ PSI experiment
1968	Scott and Ko publish Darcy Law modeling on Edwards AFB/Surveyor engine test[4]; theoretical treatment of LaRC tests[6]		Surveyor VII mission lands
1969	*Citations at end of presentation*	Second Technical Report written on PSI tests at the LaRC vacuum sphere[7]	Apollo 11, 12 missions land

Apollo-Era Testing



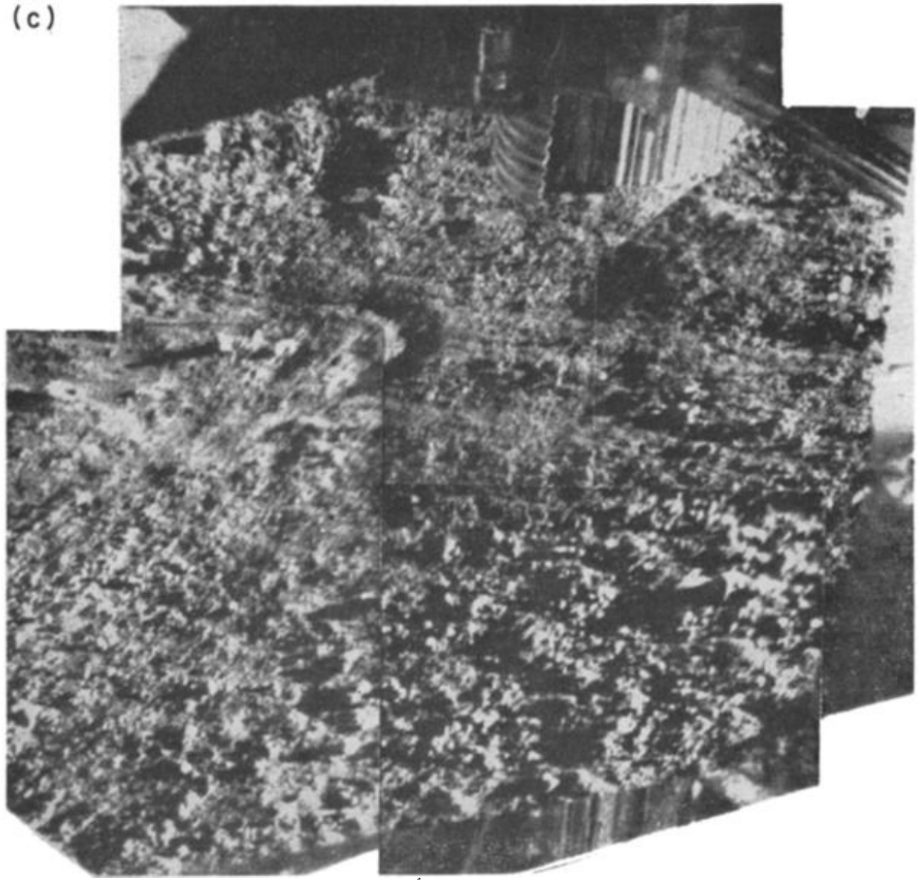
Historical testing at NASA Langley Research Center



Land and Scholl (1969)

Apollo-Era Flight Data

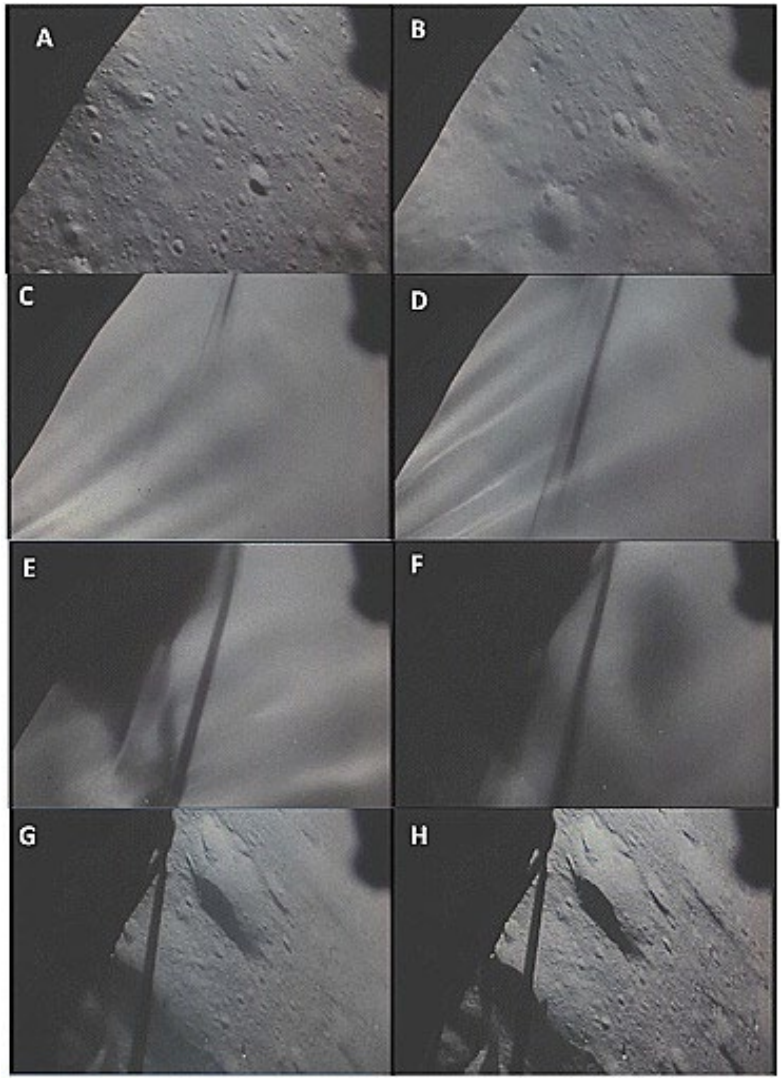
- Plume-surface interaction experiment on the lunar surface
  - Surveyor 5 vernier engine fired, images taken before and after
  - Eroded volume estimated from images; lunar permeability estimated using method from Scott and Ko (1968)



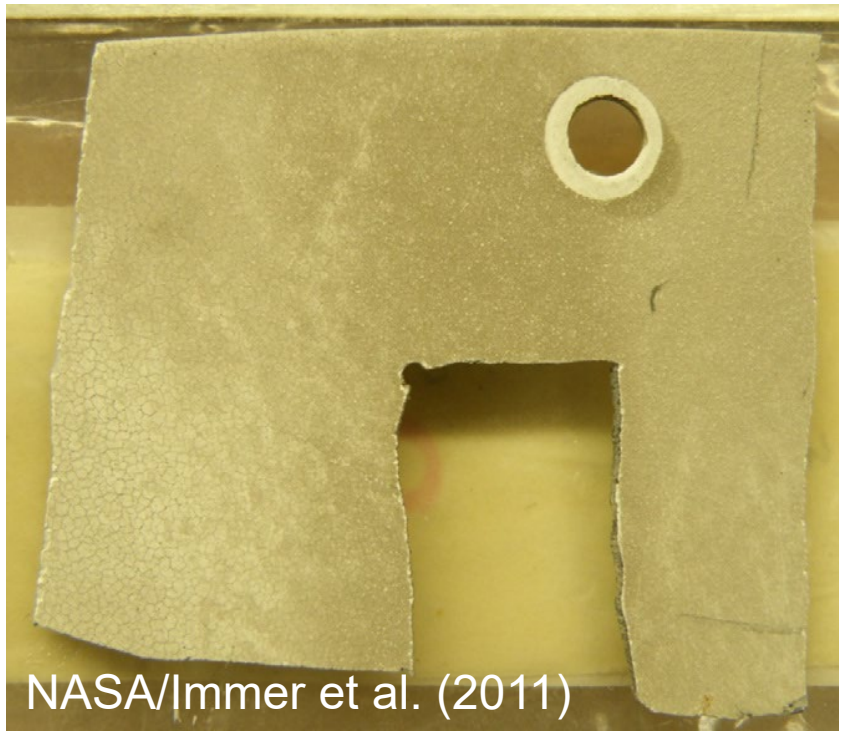
Lunar surface beneath Surveyor 5 after an engine static fire (Christensen et al., 1968)

Apollo Flight Data

Apollo landing videos show erosion, visual obscuration



Images from Apollo 15; figure from Metzger et al. (2011)



NASA/Immer et al. (2011)

Apollo 12 astronauts recovered damaged samples from Surveyor III

Apollo-Era Modeling and Mechanisms

- Erosion model proposed by Roberts (1962)
- Gas diffusion modeled by Scott and Ko (1968), used to estimate lunar permeability and grain size (Christensen et al. 1968)
- Mechanisms identified during Apollo era summarized by the Viking *Site Alteration Effects* report (Romine et al. 1977)
  - Viscous erosion
  - Diffused gas erosion
  - Bearing capacity failure

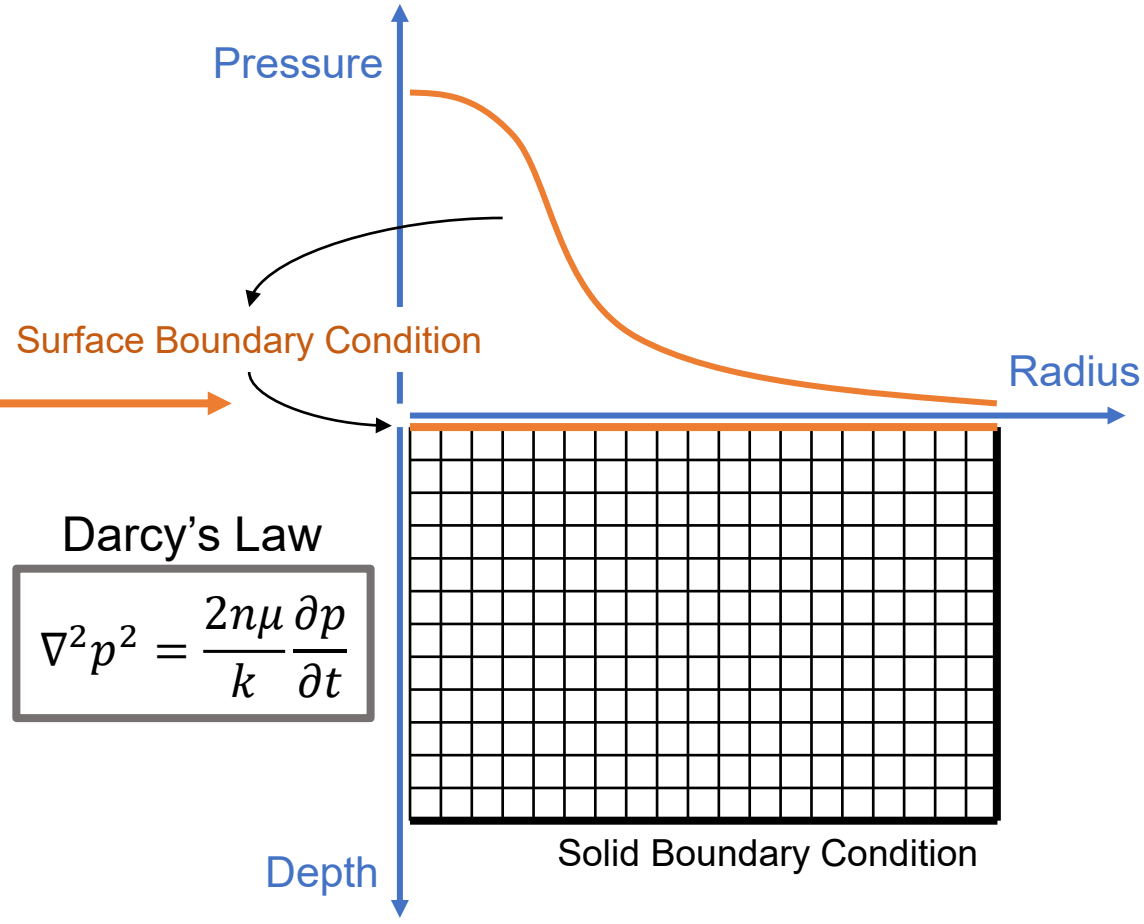
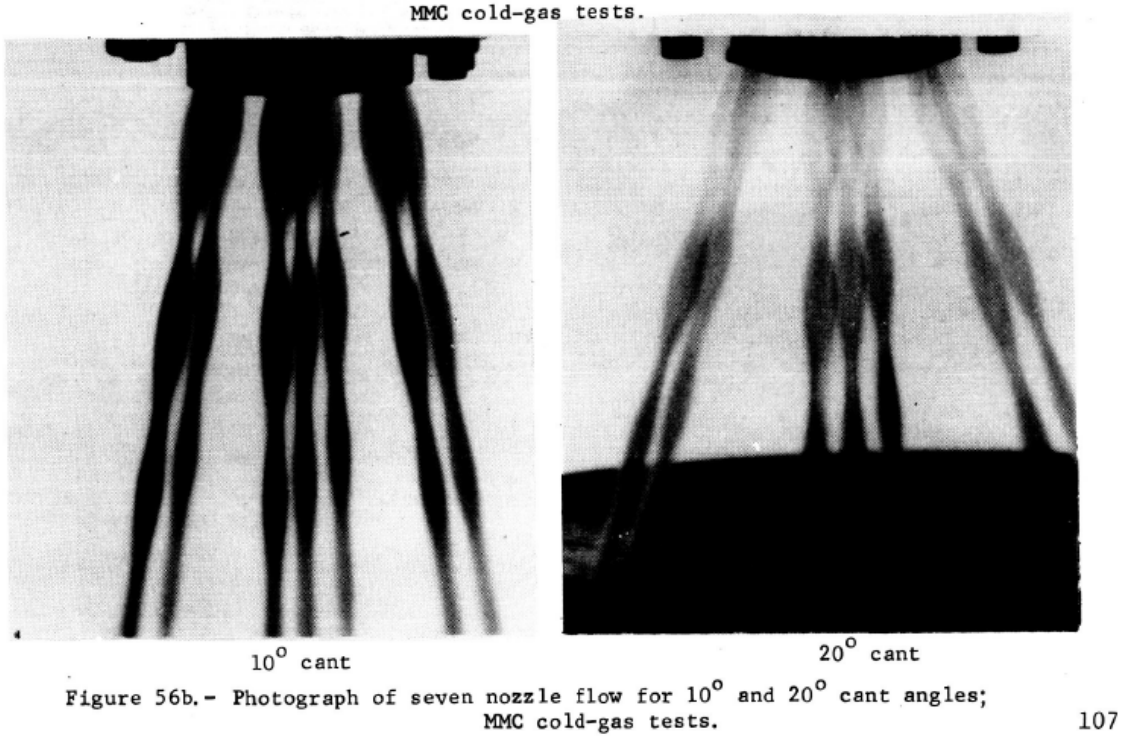


Illustration of the numerical method to estimate rocket exhaust flow in soil found in Scott and Ko (1968).

Viking PSI Research

- Summarized by the Romine et al. (1977) *Site Alteration Effects* report
- Tested multiple nozzle configurations to reduce PSI effects for Martian landing
- Drove design of Viking engine configuration and established impingement pressure limit still used today



Cold-gas nozzle testing; figure from Romine et al. (1977)

Research Since Apollo and Viking

Modern techniques, experiments, and modeling

Erosion Rate Estimation from Apollo Descent Video

- Ejecta video analyzed to estimate Apollo mass erosion rate
- Image histogram matching technique used to determine optical extinction
- Apollo 12 mass erosion estimate: 2600 kg

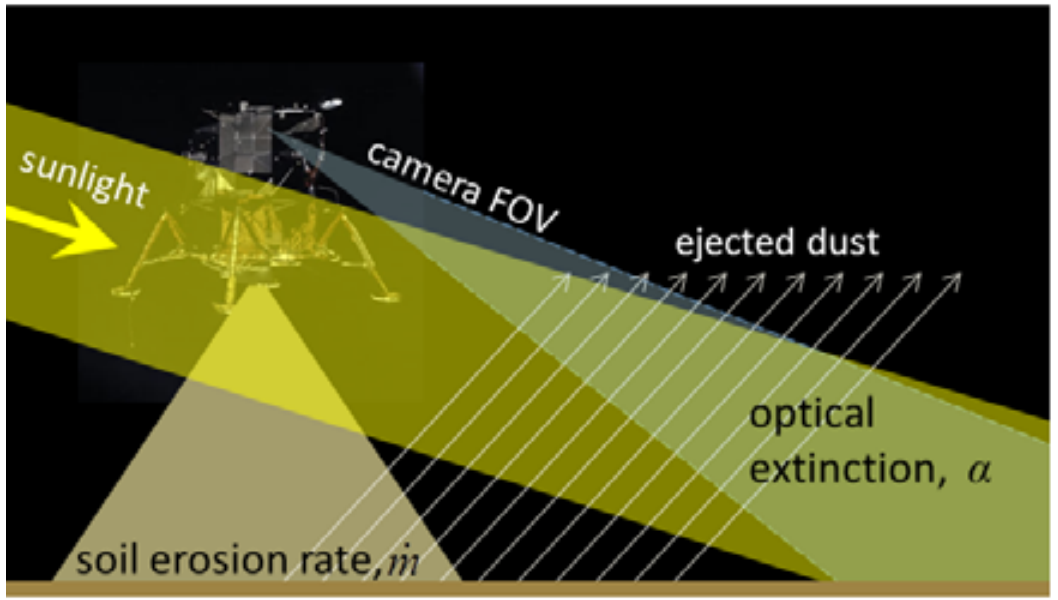


Figure from Lane and Metzger (2015)

Apollo Cratering Characteristics and Mass Estimation

- Metzger et al. 2009 identified discrete eroded layers in Apollo imagery
  - Phenomenon also seen in Mauna Kea test
- Also observe “erosional remnants”: surface features caused by PSI
- Eroded mass estimate from crater images: 1800 kg

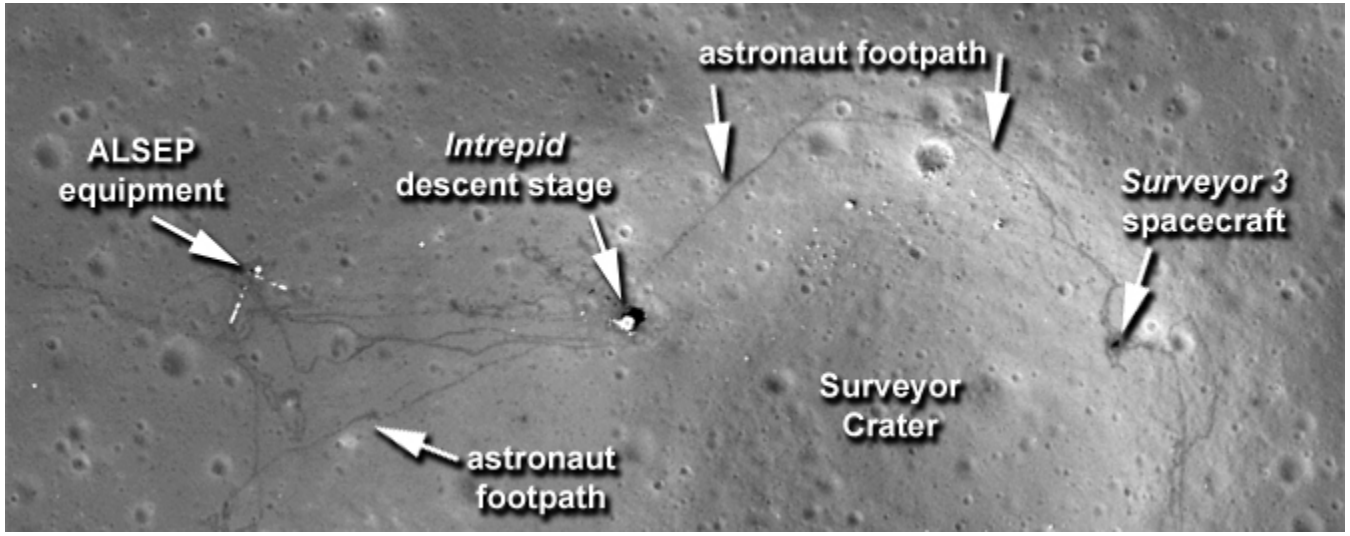
High estimate uncertainty means we can't rely on Apollo experience alone



Image: NASA/Apollo 11; annotations partially replicated from Figure 9 in Metzger et al. 2009 which show boundary of eroded layer

Lunar Surface Alteration

- Descent engine plumes had a significant effect on the Apollo, Luna, and Surveyor landing sites
- The effects of rocket exhaust on the lunar surface appear as photometric anomalies in Lunar Reconnaissance Orbiter Narrow Angle Camera imagery (Watkins, 2015)



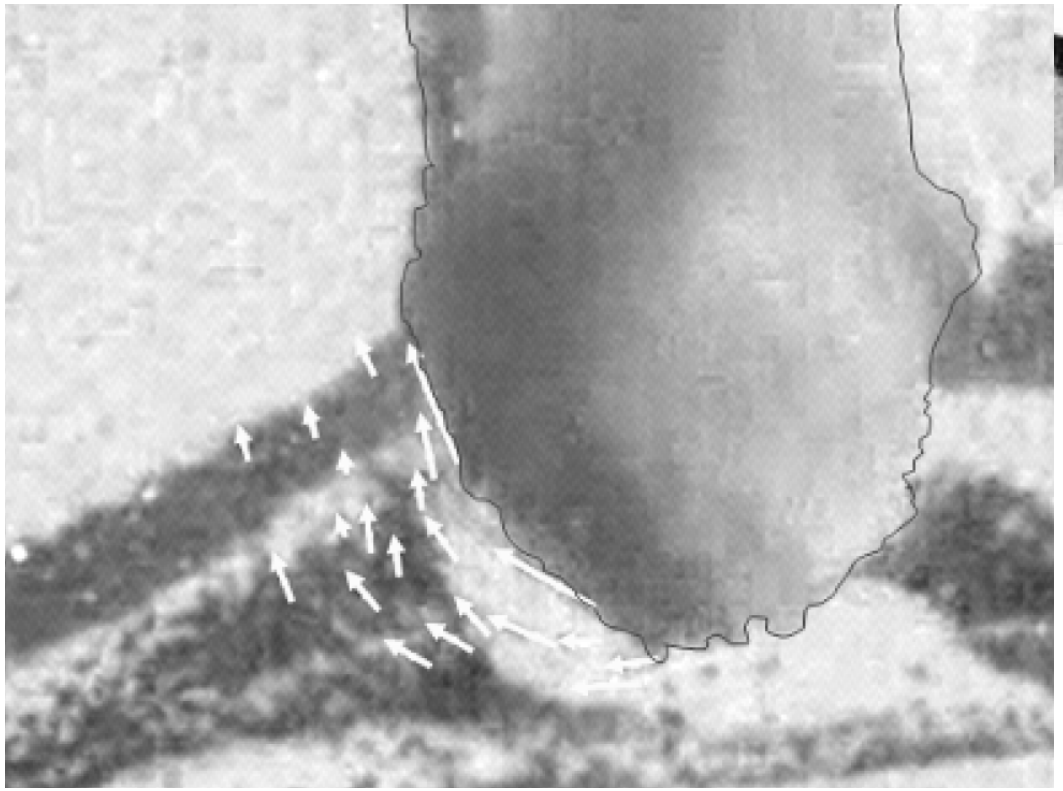
NASA/Goddard Space Flight Center/Arizona State University

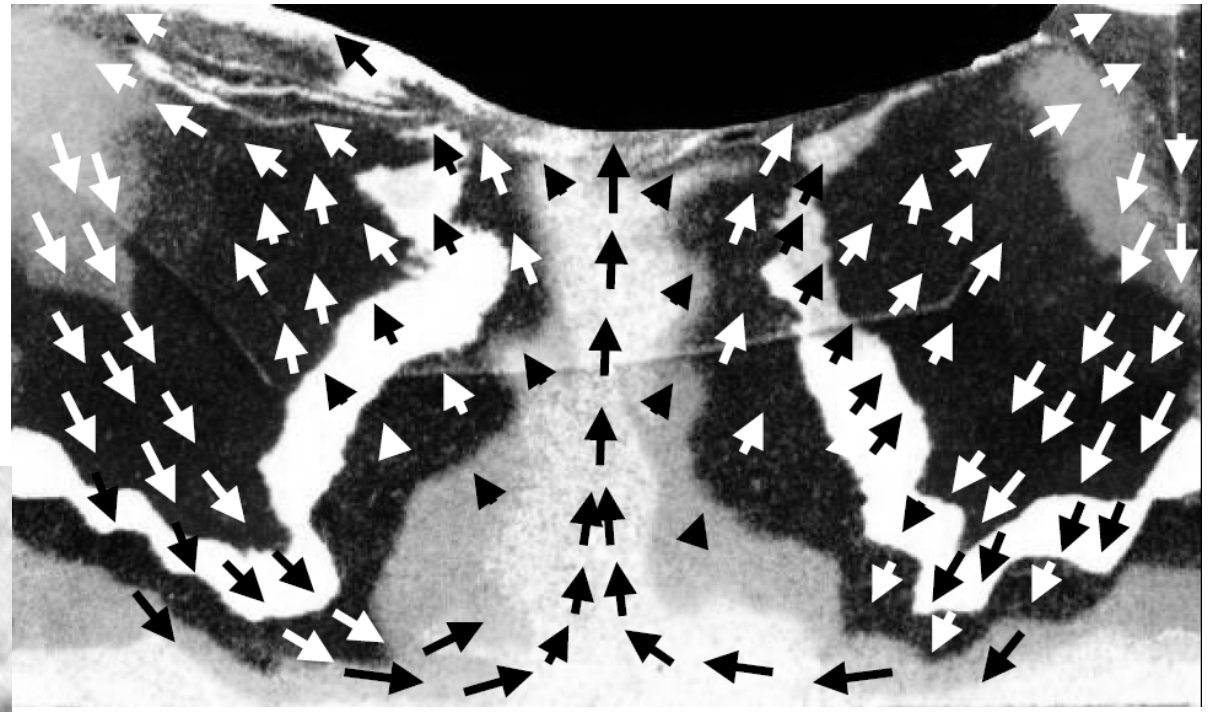


Buzz Aldrin, footpad, and disturbed area, including possible exhaust brightening right to left (behind Aldrin)

PSI Testing: Diffusion-Driven Flow

Images from Metzger et al. 2009.





Layers of sand modified by PSI; arrows show direction of motion

Diffusion-driven flow parallel to the developing crater's surface

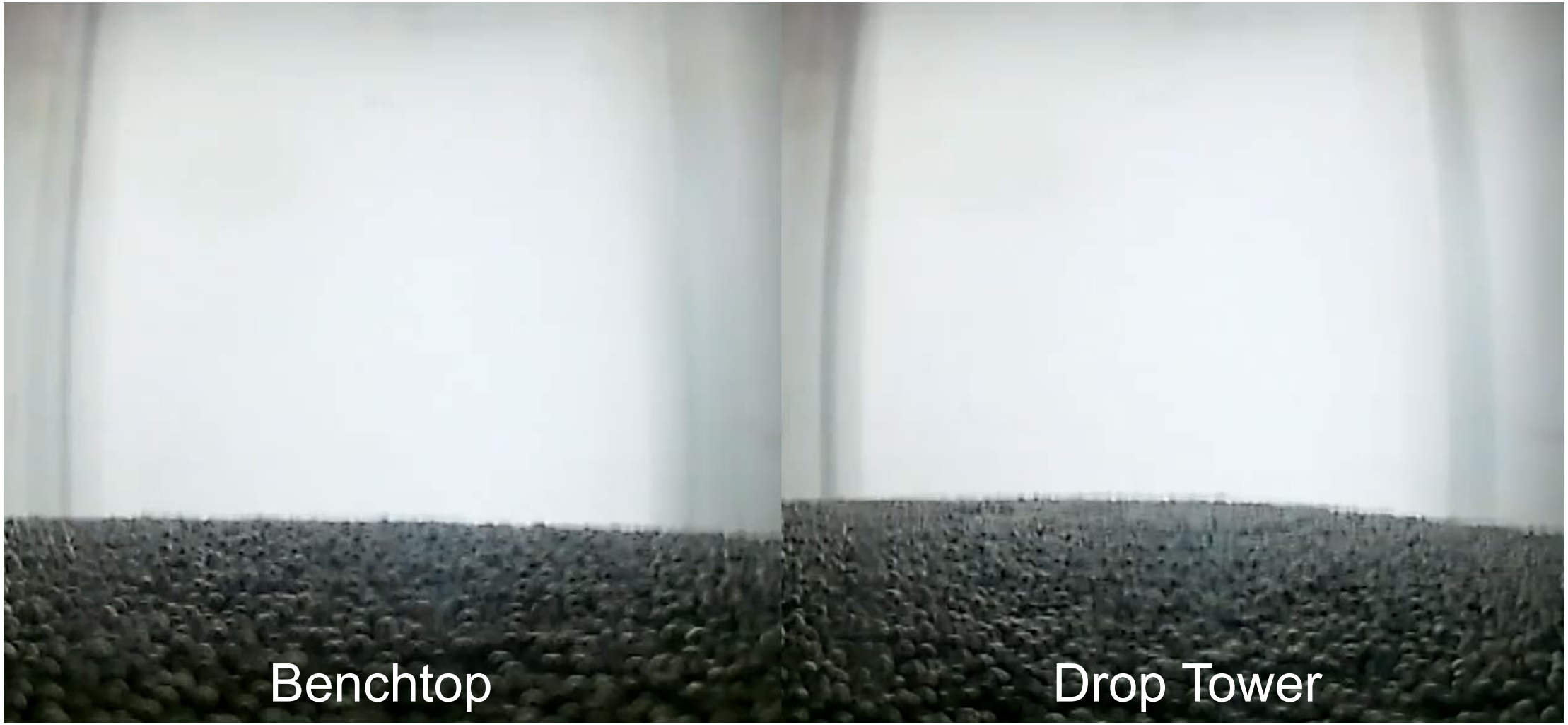
PSI Enhancement from Pulsed Jets



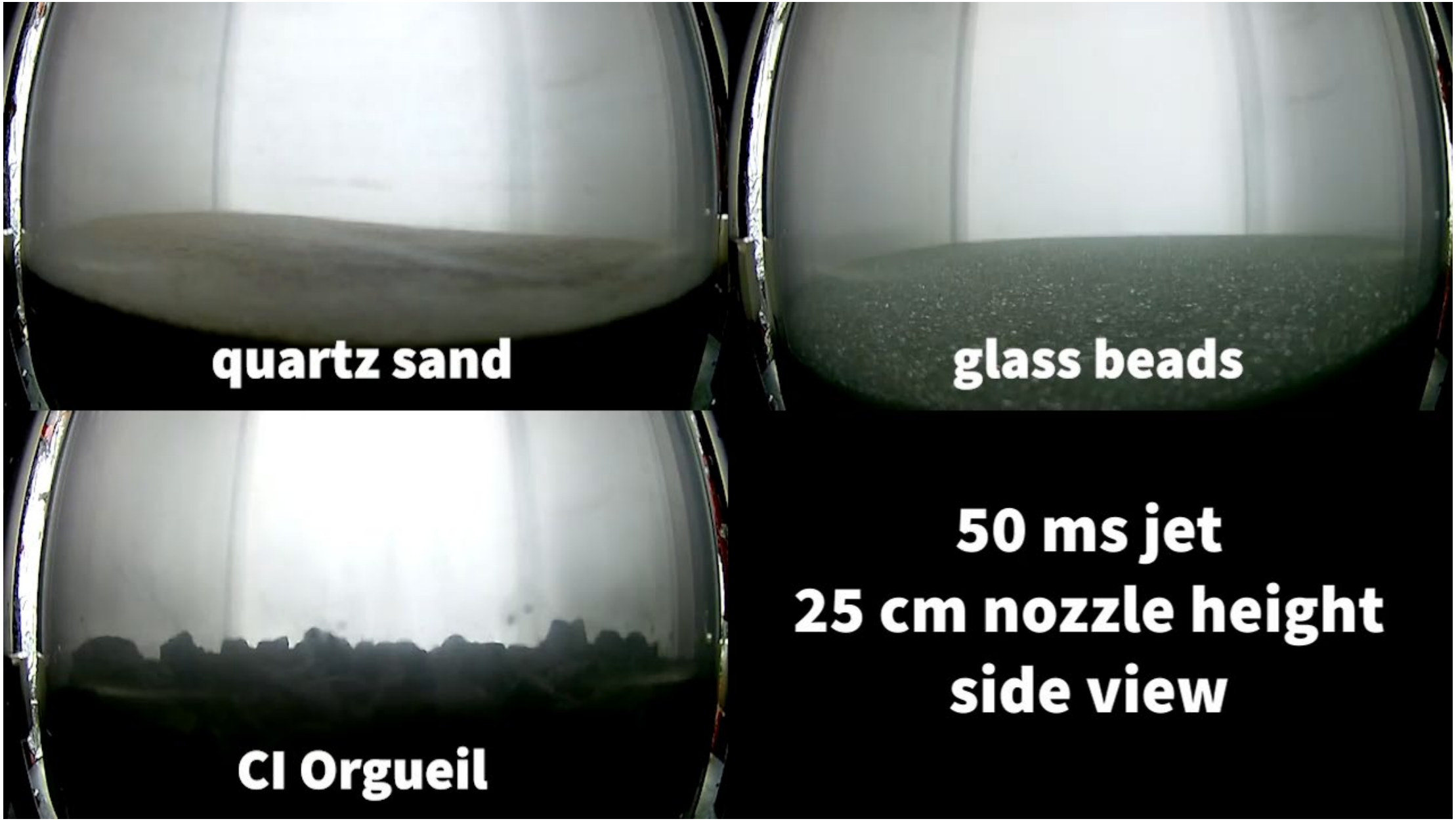
Image underneath the Phoenix Mars Lander, taken on Sol 5. (NASA)

- Mars Phoenix engines exposed ice underneath lander (Mehta 2011)
- Experiments conducted by to simulate landing
  - Pulsed jets cause enhancement of plume-surface interaction effects, leading to “explosive erosion” (Mehta 2011)

Effects of Reduced Gravity on PSI



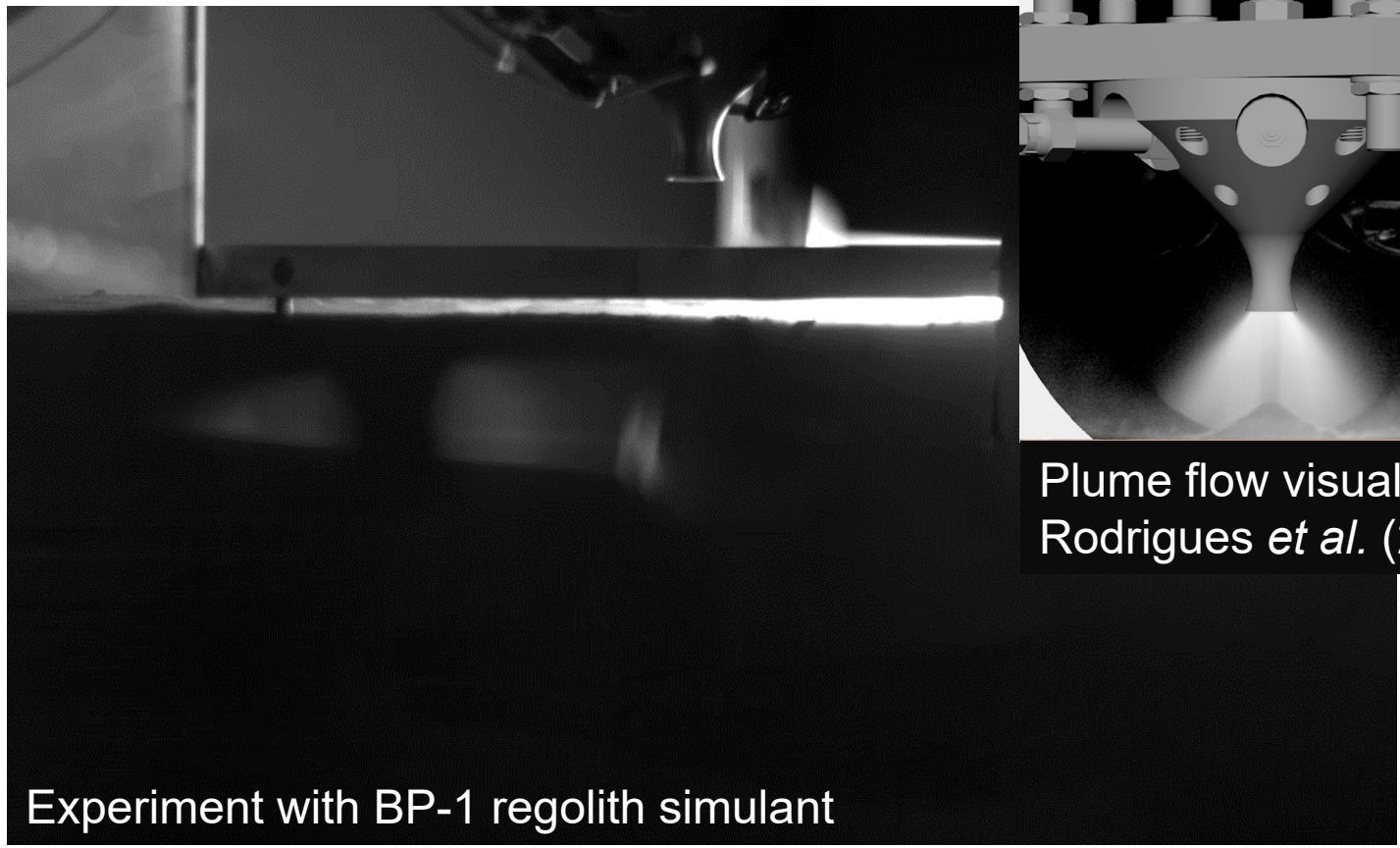
UCF/CLASS/Chambers



UCF/CLASS/ Chambers

NASA Plume-Surface Interaction Test

- Subscale, half-space, supersonic plume-surface interaction test
- Six regolith simulants, variable mass flow rate, variable vacuum pressure
- Variations in behavior observed across parameter space
- Analysis ongoing



Experiment with BP-1 regolith simulant

Plume flow visualization
Rodrigues *et al.* (2023)

Test overview: https://doi.org/10.2514/6.2022-1811

Computational Modeling

- Generalized PSI modeling remains a challenge due to complex physics
- Range of methods applied
  - Simplified/semi-empirical
  - One-way coupled CFD
  - Two-way coupled CFD
- Approaches
  - Eulerian-Eulerian
  - Eulerian-Lagrangian

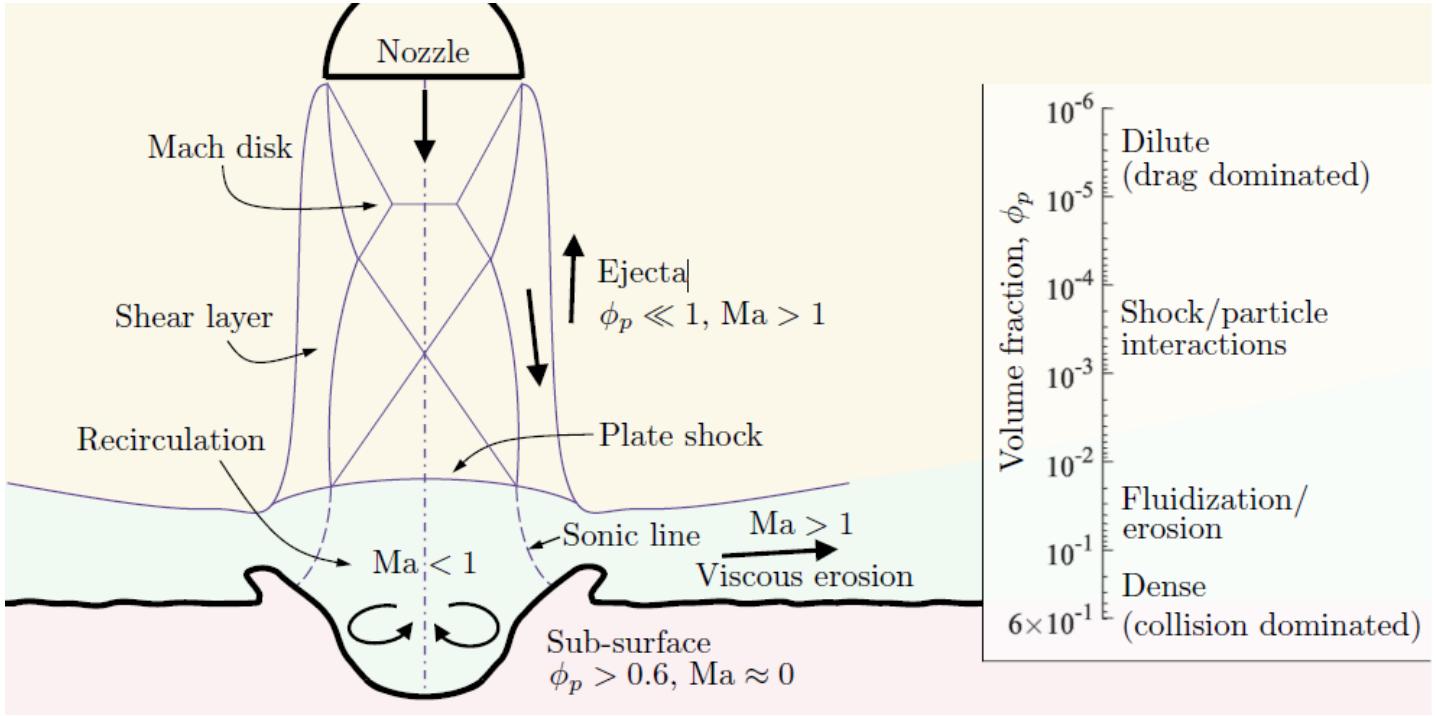


Illustration of flow regime variation, which results in challenges for PSI modeling. Figure from Capecelatro (2022), (CC BY 4.0).

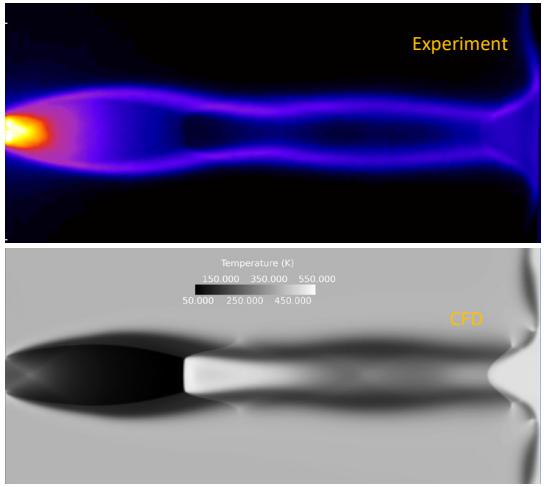
Present and Future Work
at NASA and around the world

Current PSI Research Efforts

- Auburn University
  - Vacuum chamber PSI testing, stereo diagnostics
- JAXA
  - PSI drop tower experiment and effects modeling
- Johns Hopkins University
  - Experimental/modeling work on particle-laden flows
- NASA
  - PSI testing, flight instrumentation, computational modeling of PSI effects
- Stevens Institute of Technology
  - Computational fluid dynamics applied to PSI effects
- University of Central Florida
  - Ground and drop tower PSI experiments; regolith characterization
- University of Glasgow
  - Vacuum chamber PSI testing
- University of Illinois Urbana-Champaign
  - Vacuum chamber PSI testing, ejecta tomography
- University of Michigan
  - CFD modeling of PSI effects

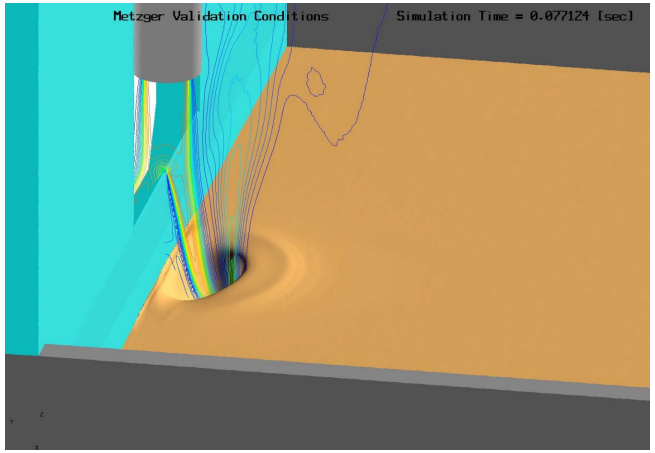
NASA Computational Modeling Efforts

Plume Flow in a Low-Pressure Environment



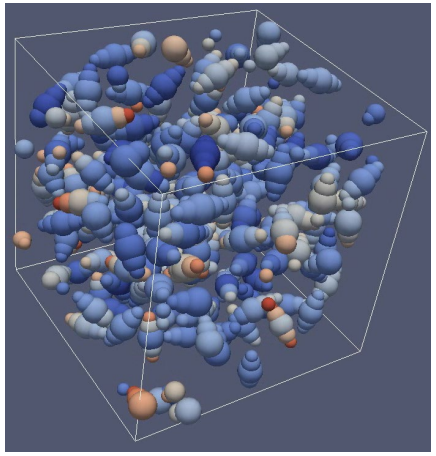
https://doi.org/10.2514/6.2022-2318

Effects of Multiple Flow Regimes



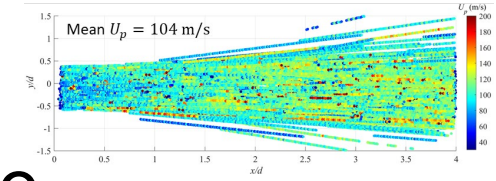
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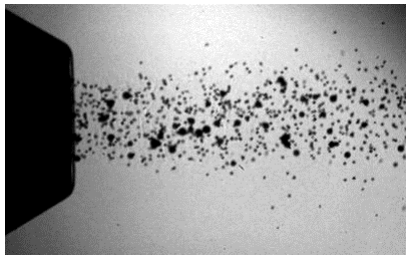
Granular Mechanics Modeling



https://doi.org/10.2514/6.2022-2317

Gas-Particle Interactions

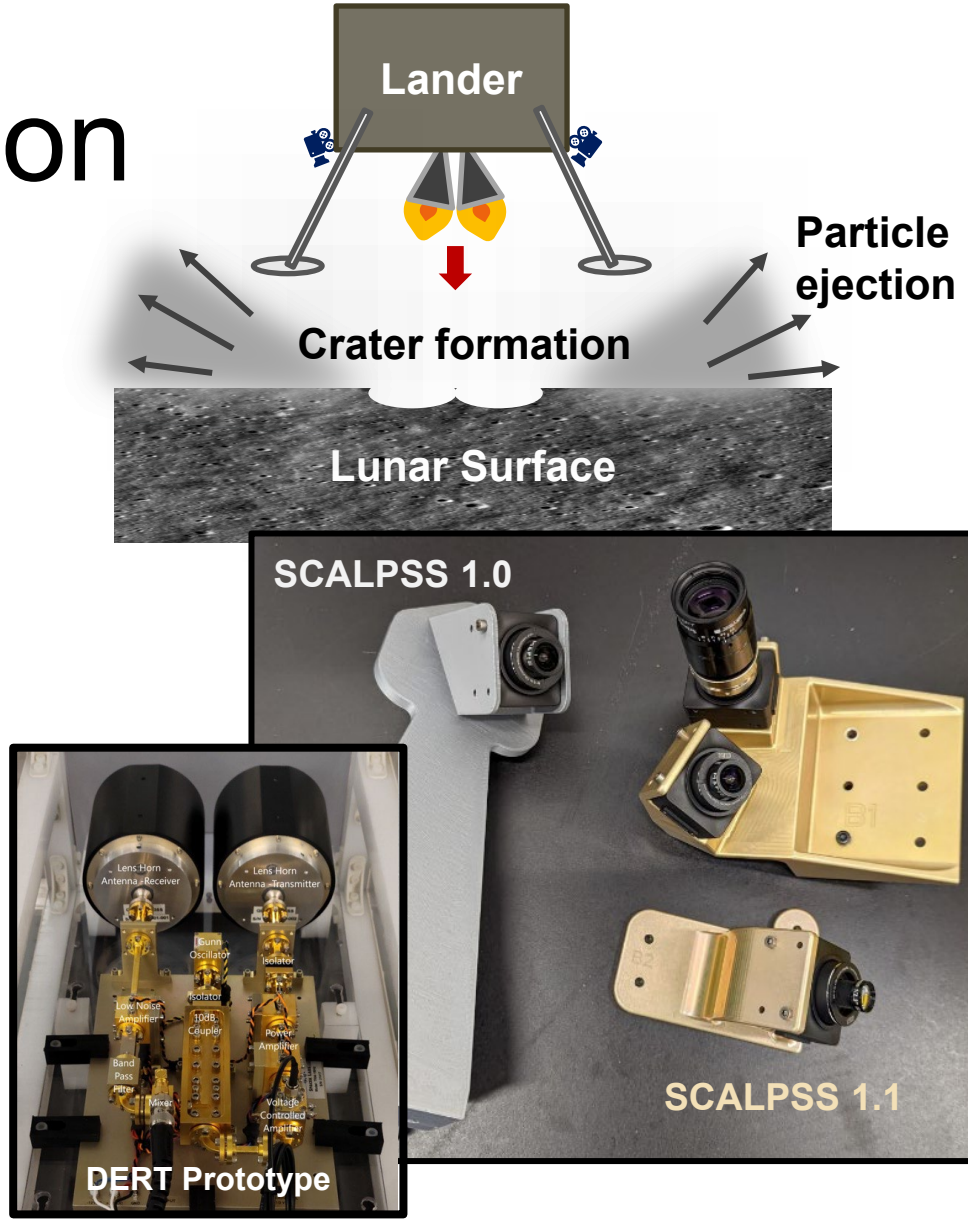




https://doi.org/10.2514/6.2020-1326

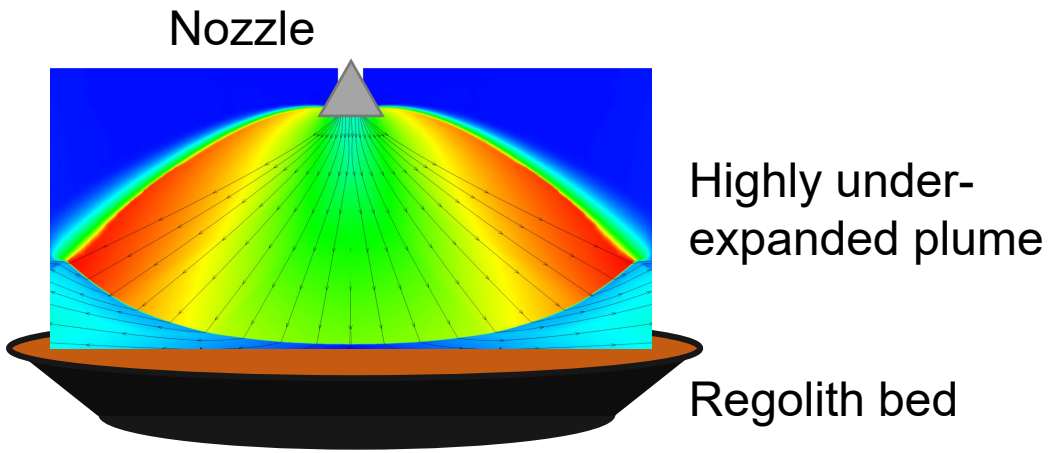
NASA Flight Instrumentation

- Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS)
  - Stereo imaging for PSI
- Lunar Lander Base Instrumentation (LLBI)
  - Measurement of environment induced below lander by thrusters and PSI, MEDLI-heritage
- Particle Impact Event Sensor (PIE)
  - Measurement of ejecta energy
- Dust Ejecta Radar Technology (DERT)
  - Millimeter-wave doppler radar measurement ejecta particle velocities
- Mini-Suite Electronics (MSE)
  - Centralized payload commanding



NASA PSI Testing for HLS Risk Reduction

- Reduce risk to the HLS Landers by acquiring lunar-relevant test data to quantify and reduce modeling uncertainty
- Targeting scaled flight conditions and an Apollo condition





60-ft Vacuum Sphere (NASA LaRC)

Conclusions

Conclusions

- PSI phenomena remain resistant to generalized modeling
- Available flight data have high uncertainties
  - Apollo remains the largest lunar lander
- Fundamental work still needed to understand plume-surface interaction phenomena and associated behaviors
- There are significant current efforts into PSI research building off foundational work from Apollo and past two decades
- Integrating these efforts will be critical to maturing the PSI discipline

Questions?

References for *Apollo-Era PSI Research* slide

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