



Rocket Plume Interactions for NASA Landing Systems

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NASA – DLR Technical Interchange Meeting



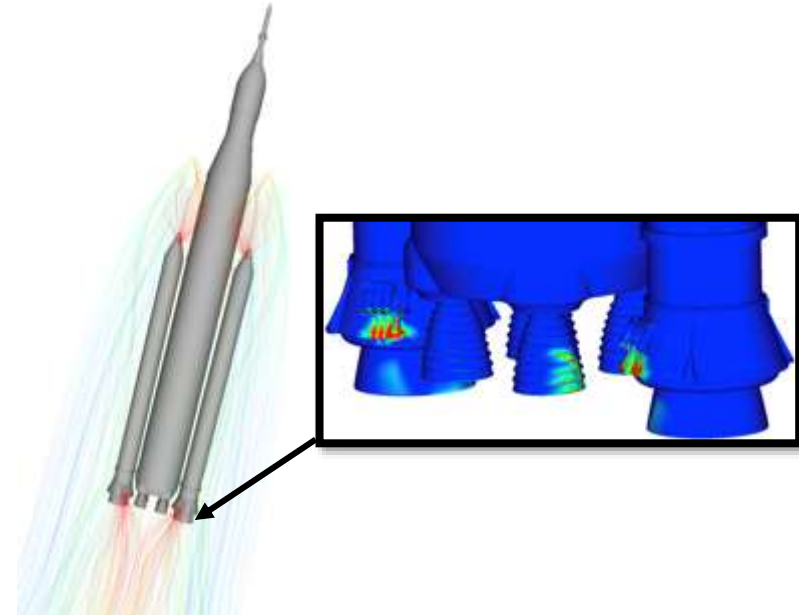
NASA Aerosciences

◆ Two main areas

- Agency makes it a commitment to fully investigate the performance and environments of their vehicles

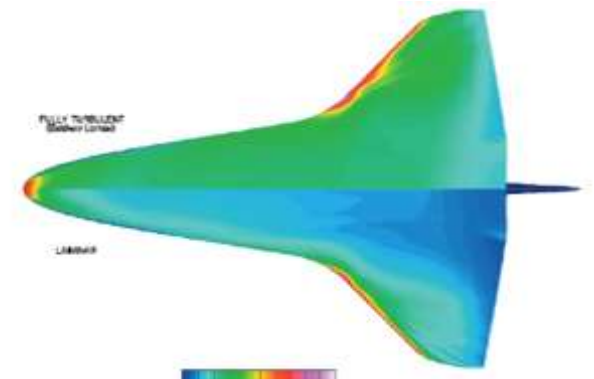
◆ Rocket plume-induced environments

- Launch vehicle & upper-stage base flows
- Lander base flows
- Plume-induced flow separation (PIFS)
- Plume impingement
 - Stage Separation Motors
 - Attitude Control Motors
 - Lander Leg Struts/Footpad
- Plume-Surface interactions (PSI)
 - Erosion Physics
 - Ejecta Dynamics
 - Plume Physics
- Plume-induced aerodynamics
 - Launch Vehicles
 - Landing Systems



◆ Aerodynamic flow environments

- Earth crew vehicle re-entry flows
 - Shuttle Orbiter
 - Apollo
- Fuel/oxidizer tank, booster element earth re-entry
 - External Tank, SRBs
- Launch vehicle ascent aerodynamic flow/heating
- Planetary spacecraft re-entry flows
 - Mars Science Laboratory (MSL)





Concept – Plume Surface Interaction (PSI)

PSI Definition:

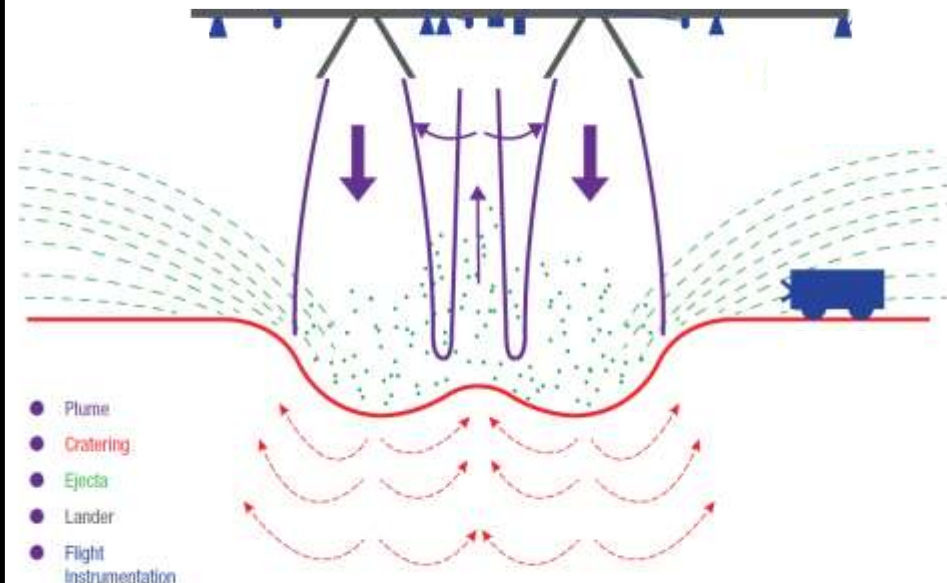
- Rocket plume-surface interaction (PSI) is a multi-phase and multi-system complex discipline that describes the lander environment due to the impingement of hot rocket exhaust on regolith of planetary bodies. This environment is characterized by the plume flow physics, cratering physics and ejecta dynamics.

Problem Statement:

- Extraterrestrial PSI cannot be accurately modeled with cold flow terrestrial testing. There are technical gaps in the physics modeling in the predictive simulation tools and ground tests. There are limited to no flight instrumentation dedicated to PSI. *An accurate, validated predictive simulation capability is required to mitigate against lunar dust environments and to land large, heavy payloads.*

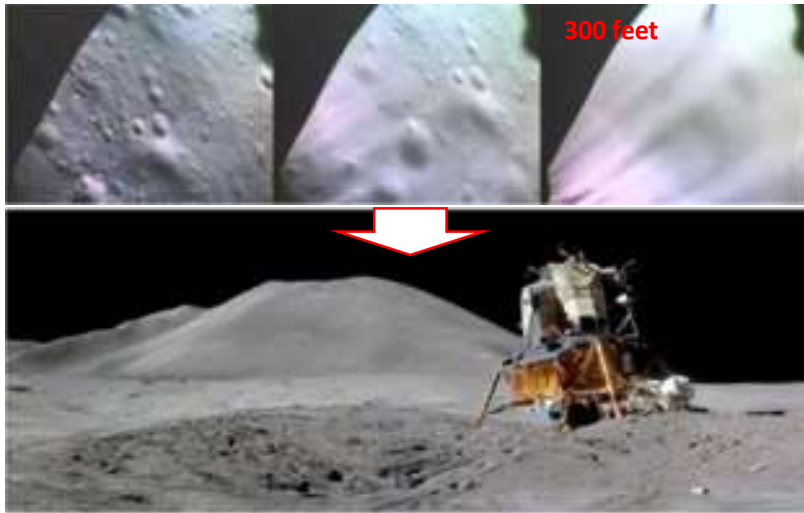
Objectives:

- Develop an integrated modeling, simulation, and testing approach to PSI definition
- Close the identified gaps in physics modeling that are first order to accurate prediction in simulation
- Perform targeted unit experiments to develop models which will be integrated into simulation tools to close gaps
- Conduct relevant small and large scale ground tests for predictive code validation and engineering model development
- Advance the state-of-the-art flight instrumentation to obtain flight data for predictive code validation

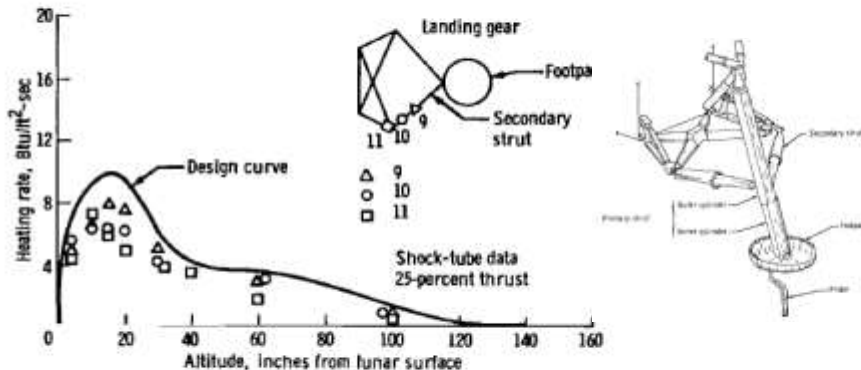




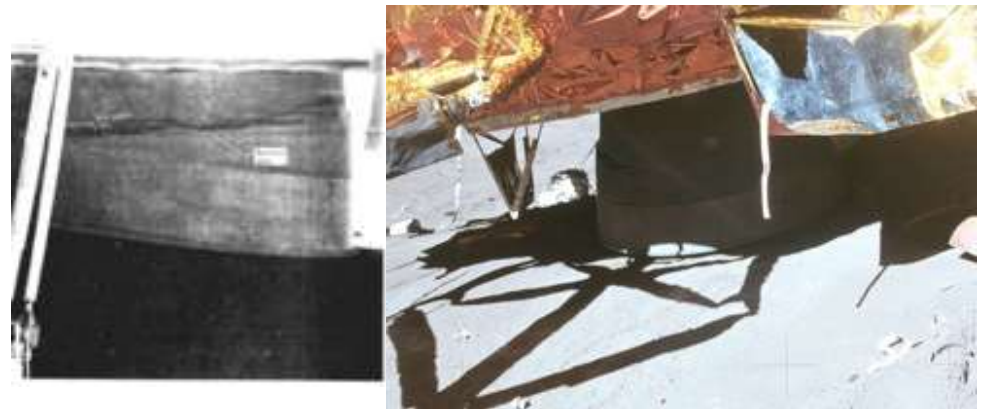
PSI Lunar Landing Risks



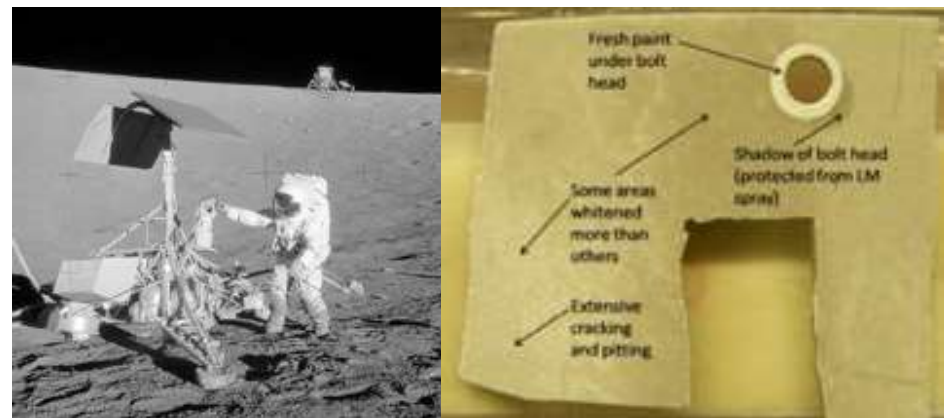
Lack of landing visibility due to rocket plume-induced erosion physics and ejecta dynamics led to a $\sim 12^\circ$ tilt (max tilt requirement) of the Apollo 15 lander with the front footpad bearing no weight. Almost led to mission failure. Four out of the 6 Apollo landings had serious visibility problems with lunar plume-induced ejecta during landing - led to flying blind



Plume heating on the lander struts was above design environments and led to thermal blanket charring for Apollo 11 - led to redesign of LEM TPS and plume shield



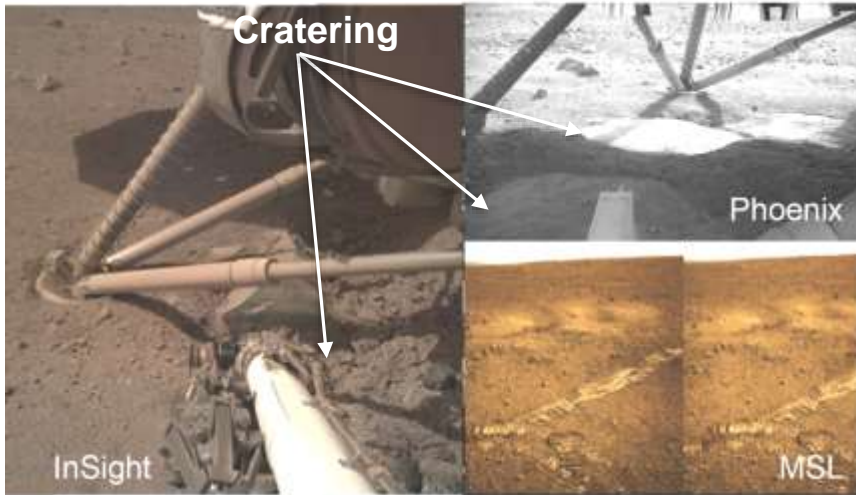
Lack of landing visibility due to rocket plume-induced erosion physics and ejecta dynamics led to close proximity of the nozzle exit plane to the crater rim. This led to the plume exhaust back-filling into the nozzle, overpressurization and buckling of the LEM descent engine nozzle skirt - structural failure



Apollo 12 rocket plume-induced ejecta sandblasting of Surveyor 3 525 feet away led to degradation of hardware. This will affect other lunar outposts, and nearby critical hardware.



Motivation: PSI Mars Landing Risks

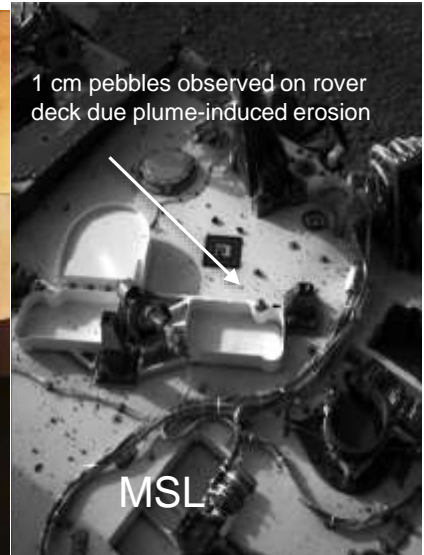


[Mars Chief Technologist Edwards Endorsement Letter] "...the 2011 Mars Science Laboratory mission suffered damage to one of its meteorological instruments during terminal descent; it is believed this damage was caused by surface debris raised by the skycrane descent rocket plume. Mars 2020 will use a similar skycrane concept, so there is strong interest in better understanding these plume/surface interactions ... "These efforts seem quite timely: the validated modeling tools will have immediate application to better assessing Mars 2020 and SRL risks, and will be of continuing interest as NASA begins to evaluate EDL options for even larger landed payloads."

Significant plume-induced site-alteration occurred on Mars due to rocket engine thrust of less than 300 lbf for the SMD landers. Proposed human Mars lander engines are on the order of 10,000 lbf and 25,000 lbf thrust. There will be extensive plume-induced erosion during human Mars landings and we have no confident method of predicting these environments.



InSight hazcam was occluded and images were deteriorated due to ejecta adhering to the lens after the dust cover was removed. Was an issue for a large part of the first 30 sols



Plume-induced ejecta dynamics led to limited landing visibility and impacts to flight instrumentation resulting in loss of function and damage.

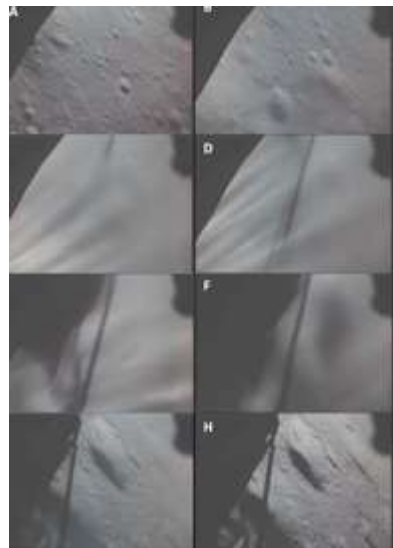


PSI Sub-Disciplines

EDL System Capability Lead has identified PSI as a major unresolved risk for propulsive landing. Recent technology interchange meetings on PSI outlined modeling and ground testing gaps. This proposal is responding to the identified need.

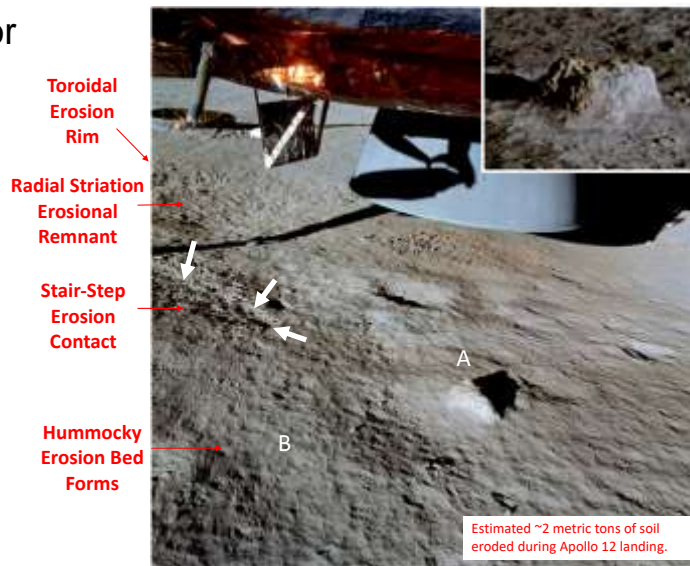
Ejecta Dynamics

- Ejecta dynamics lead to loss of instrumentation or function, damage to the lander/surrounding structure, lack of landing visibility and can spoof radar and NDL systems
- Deteriorated Apollo landing visibility, InSight initial loss of camera function and MSL sensor damage



Erosion Physics

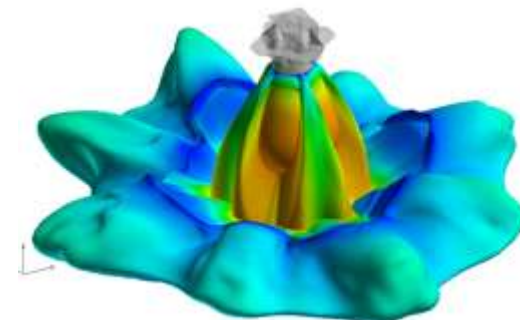
- Erosion can lead to destabilization of the lander upon touchdown and violate lander tilt requirements and damage hardware
- Apollo and InSight landers saw extensive site-alteration



Apollo 12 Metzger (2010)

Plume Physics

- Plume effects on the lander can lead to aerodynamic destabilization and high convective heating during powered descent and landing
- V-22 Osprey and Harrier failures



Liever (2019)



Benefit and Impact – PSI

Benefit of Proposed Work: Provides tools and data to predict the environments that enable smart design and risk analysis of EDL architectures driven by PSI. With this work, NASA will be able to predict landing environments and develop mitigating strategies.

Impact:

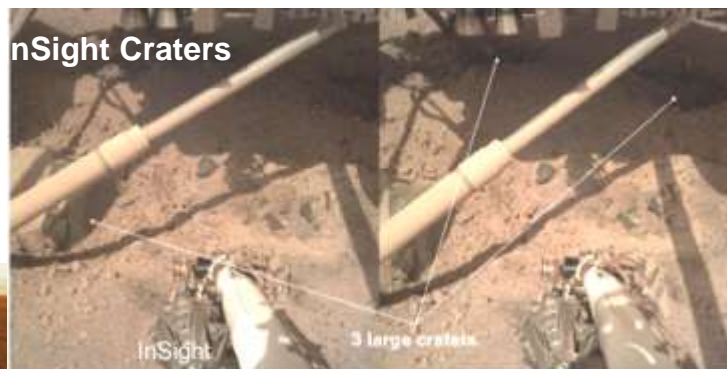
- Identifies environments and ejecta transfer and strikes
- Reduces design uncertainty due to landing environments
- Informs instrumentation/hardware placement & protection
- Informs lander system design requirements
- Identifies keep-out zones
- Defines landing visibility threshold requirements & mitigations



Apollo 15 LEM camera views showing progression of plume-regolith interaction resulting in high speed particle sheets obscuration. (Metzger, 2011)



Debris on top of MSL



InSight Craters

InSight

3 large craters



Regolith dust cloud formation during Morpheus lander plume impinging on Mars simulant (Morpheus, 2013)

MSL Skycrane Plume Induced Surface Cratering

Sleepy Dragon

Hepburn

Burnside

Goulburn





Urgency– PSI

◆ Current State of the Art and Past Experience

Limited and **large uncertainty** data from Apollo imagery | **Limited accuracy** and application of PSI semi-empirical tools | **Gaps** in some of the physics modeling of high-fidelity PSI computational codes | **Lack of relevant ground test** data (hot-fire, flight-scale, reduced atmosphere) | **No** PSI dedicated flight **instrumentation** | **No coordinated approach** within this discipline | **Not historically considered** as a vehicle design environment

◆ New Insights

- Modern computational methodologies create the opportunity to develop and mature high-fidelity predictive simulations with a high level of accuracy
- Two simulation tools have been identified as basis for research and production applications: JPL Code and Gas Granular Flow Solver (GGFS, CFDRC/MSFC).
- Foundational development of physical models and predictive simulation tools through SBIRs, STTRs, grants, Technology Investment Programs (TIPs), Center Investment Funds (CIFs), and some direct project funding. Promising results.
- Testing infrastructure now exists to conduct relevant PSI ground test at reasonable cost
- CLPS provides frequent opportunities to collect flight data; PSI-dedicated flight instrumentation is being proposed around the Agency and SCALPSS has been awarded

◆ Urgency: Agency has committed to human-scale Lunar landers by 2024

- Focus of this work will be on Lunar landing. This is a Moon-to-Mars capability applicable to both the Moon and Mars landing systems.

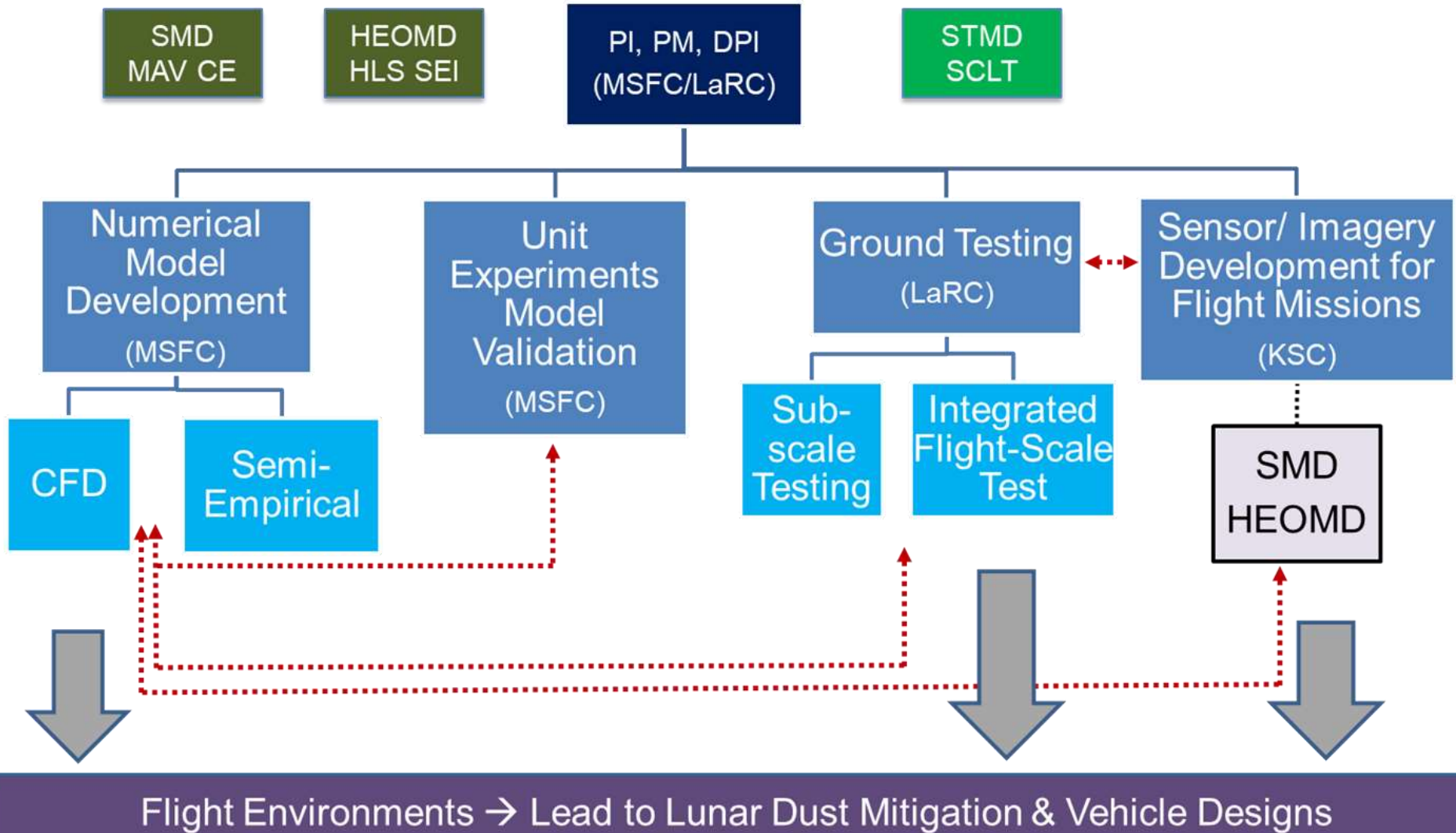


Critical Technology & Risks – PSI

- ◆ **In order to advance the predictive simulation technology, an integrated analysis and testing campaign must be established.**
- ◆ **For this proposal, a team has been assembled to**
 - Develop, mature, and validate PSI predictive models and simulation tools
 - Execute unit physics experiments
 - Execute tests at realistic scales and environments to inform model development and validate simulation tools
 - Develop PSI dedicated flight instrumentation capability
- ◆ **For this proposal, targeted advancements were chosen that represent First Order effects in PSI prediction accuracy, can be accomplished in four years, and can demonstrate improvement each year**
- ◆ **The outcome of the work from this proposal will be**
 - Production predictive simulation capability ready to support Lander programs with a focus on Lunar
 - Improved models that can be input into research and application predictive simulation tools
 - Terrestrial data sets with realistic environments & scale that can be used for code validation and semi-empirical model development
 - Advancement in flight instrumentation to target PSI
- ◆ **Predictive simulation tools will also be available to validate against lander flight data**
- ◆ **Technical Risks & Mitigation Strategies**
 - Modeling and simulation – Extracting required data from terrestrial experiments at relevant environments for model development and validation
 - Hot-fire rocket plume – regolith interaction test programs in vacuum needs to have infrastructure put in place, but have reduced risk by identifying facilities that can incorporate this infrastructure at low cost
 - No test facility will be able to simulate lunar atmosphere or gravity, but can mitigate risk by approaching Mars environments and running sensitivity studies
 - Able to obtain measurements that can directly feed into computational models
 - Improve the TRL for PSI flight instruments, but are leveraging LOFTID, M2020 & MEDLI to reduce risk



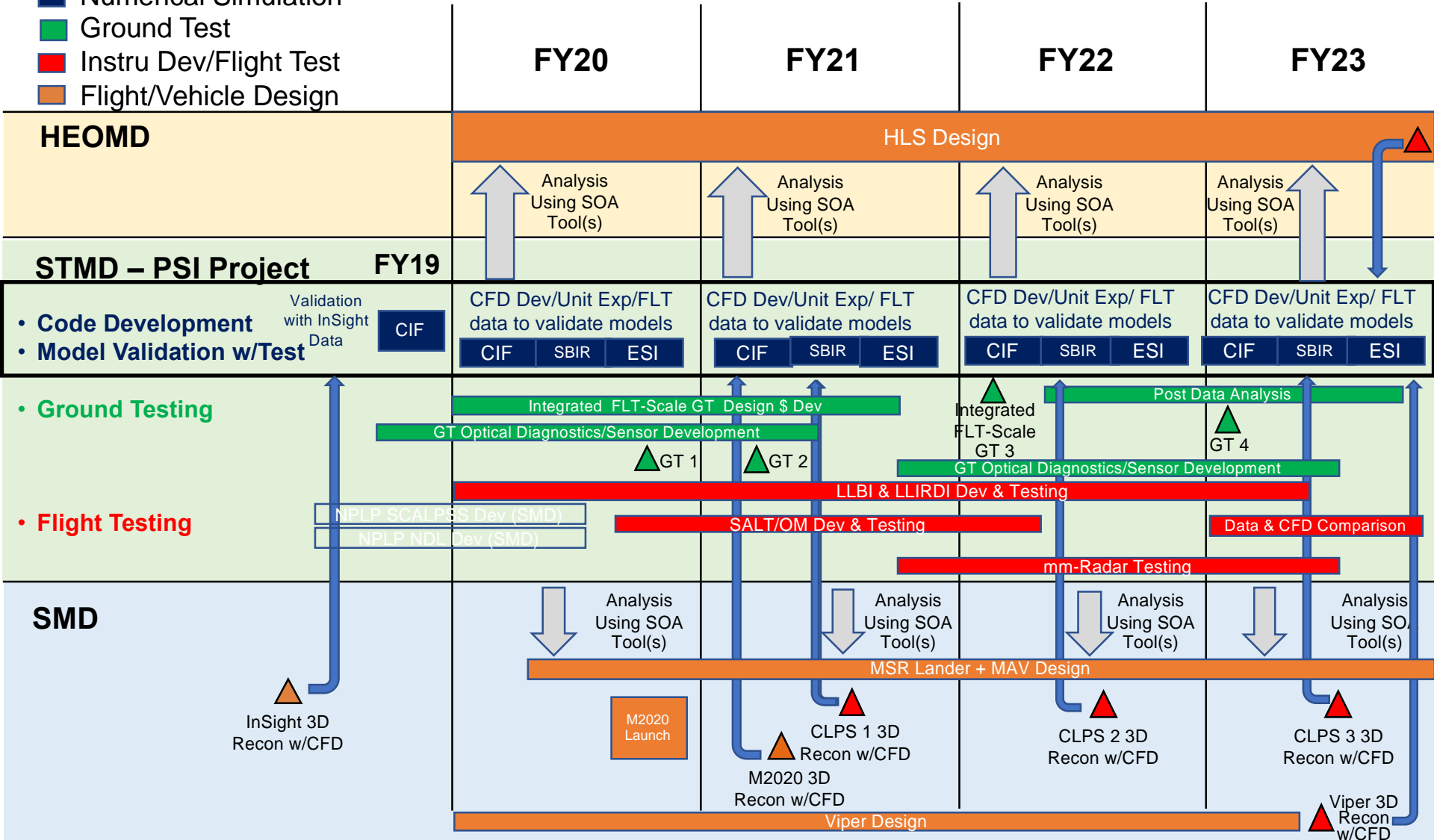
STMD GCD PSI Project Structure





PSI – High-Level Schedule

- Numerical Simulation
- Ground Test
- Instru Dev/Flight Test
- Flight/Vehicle Design

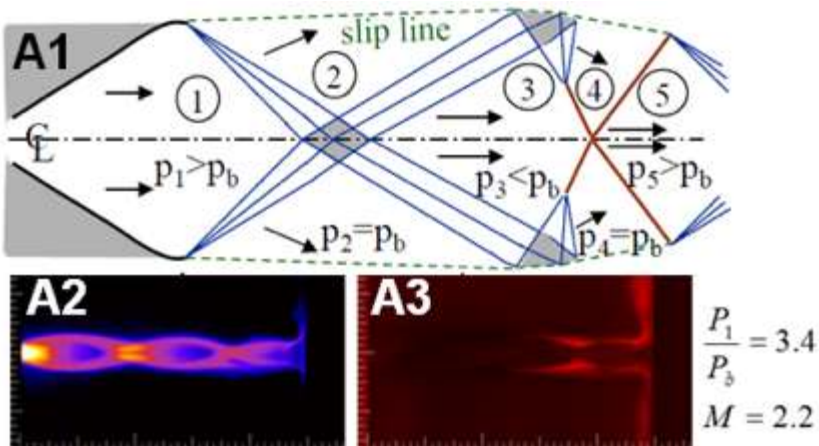




Near-field flow

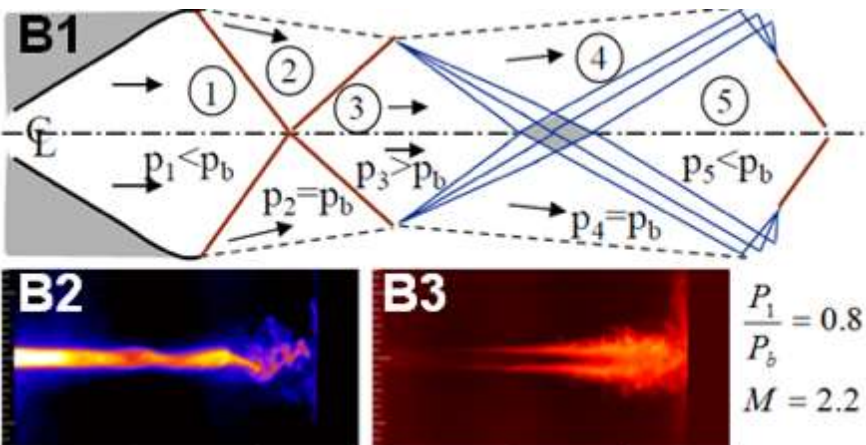
Far-field flow/ Impingement zone

Underexpanded Supersonic Jet



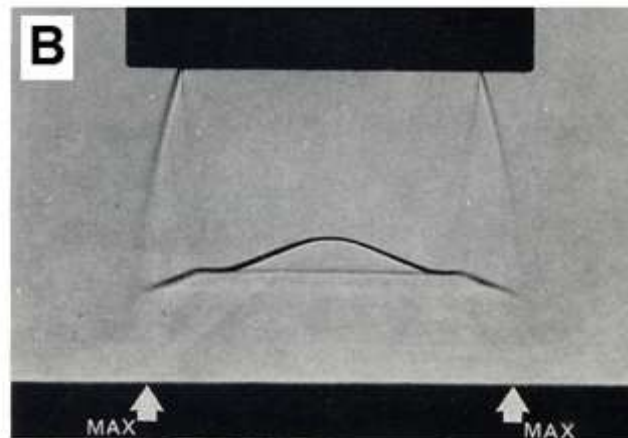
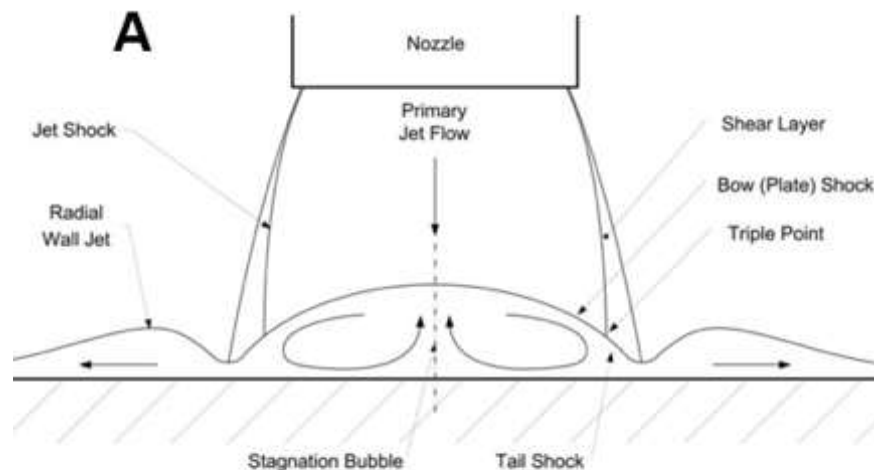
Planar Laser Induced Fluorescence Imaging

Overexpanded Supersonic Jet



Inman et al., 2009

Important flow structures with implications to cratering, acoustics and spacecraft dynamics during descent

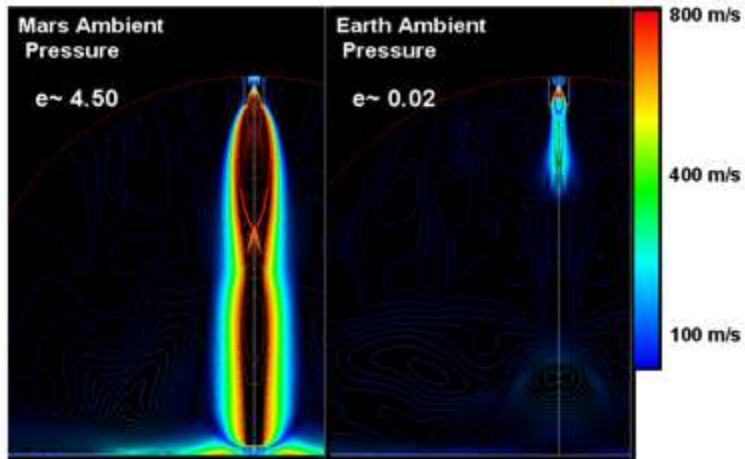


Lamont and Hunt, 1976



Jet expansion ratio

CFD – Mach Contours



$e = 4.50$

$e = 0.02$

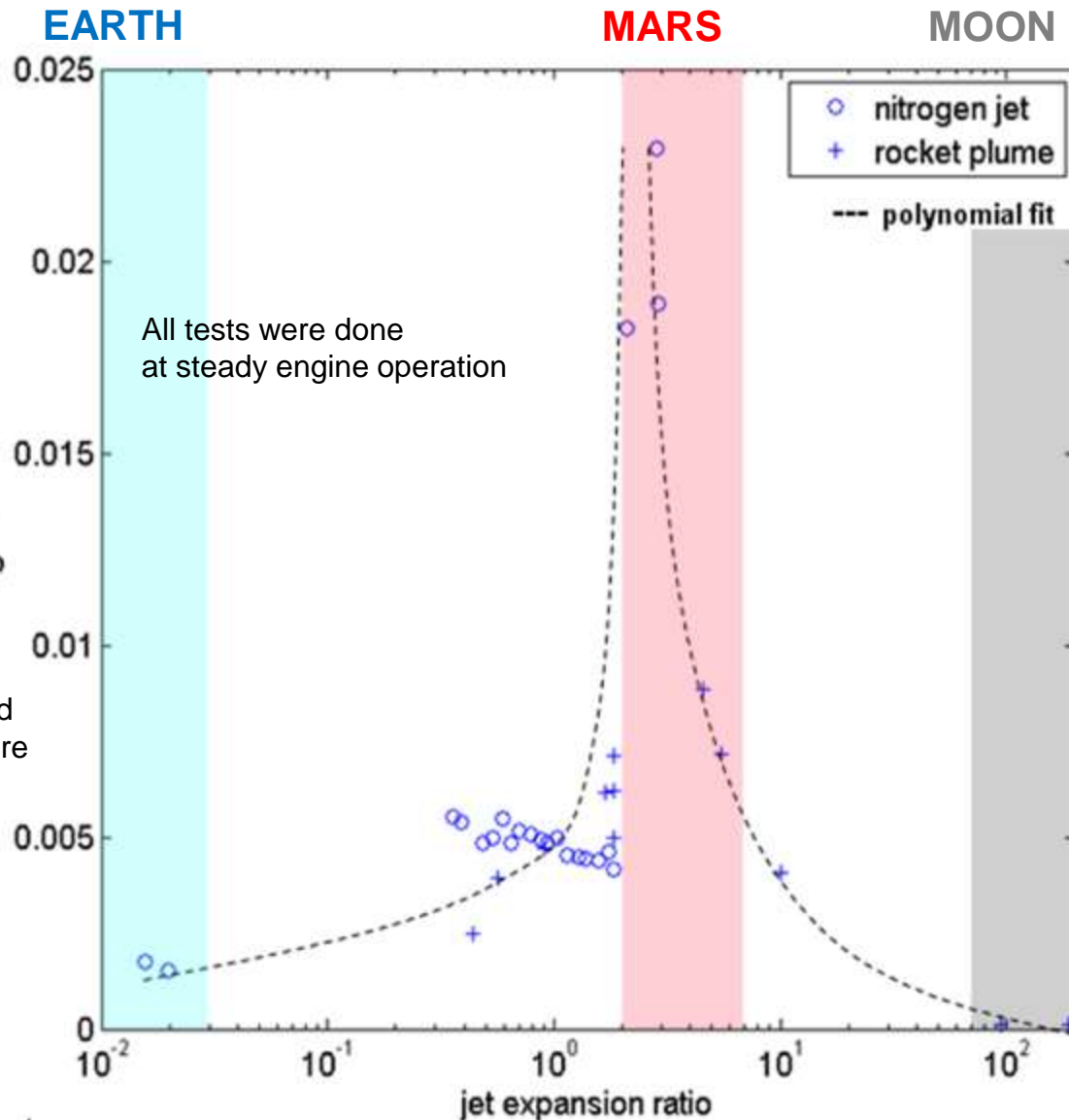
Mars – max ground pressure loads due to collimated plume structure and development of a small areal plate shock

Earth – highly overexpanded plumes dissipate/no plate shock formation

Moon – highly underexpanded plumes leads to a large areal plate shock – decreases ground pressure

Max normalized ground pressure

P_g/P_c

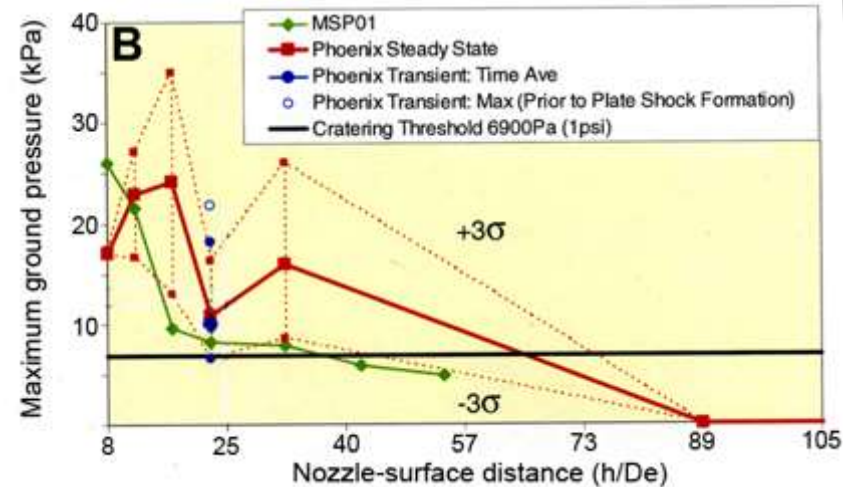
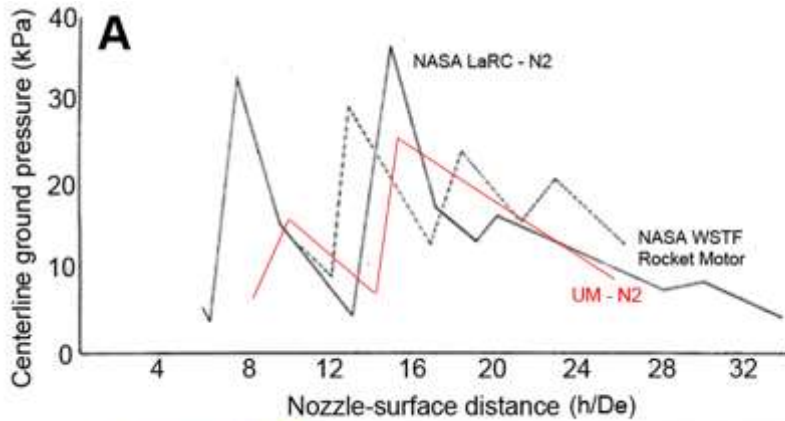




Other shock interaction effects during spacecraft landings

Altitude Effects

Ground pressure vs normalized altitude

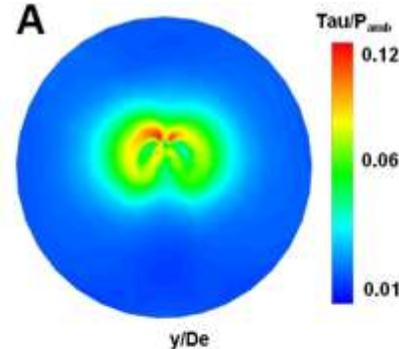


GASP

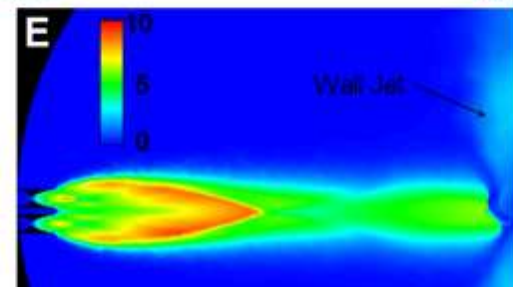
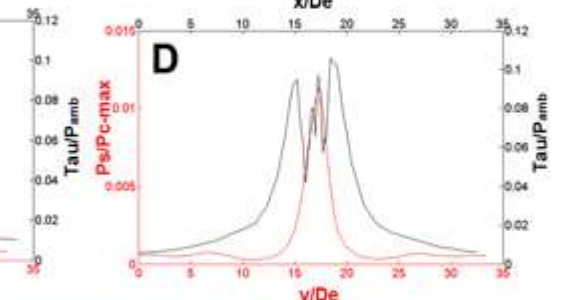
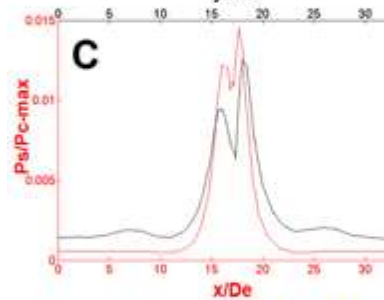
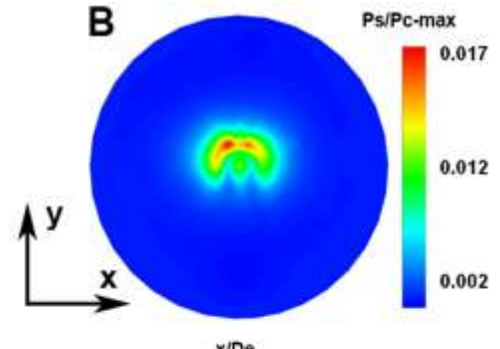
Gulick et al, 2006

Spatial Asymmetry

SURFACE SHEAR STRESS



SURFACE PRESSURE



MACH CONTOUR

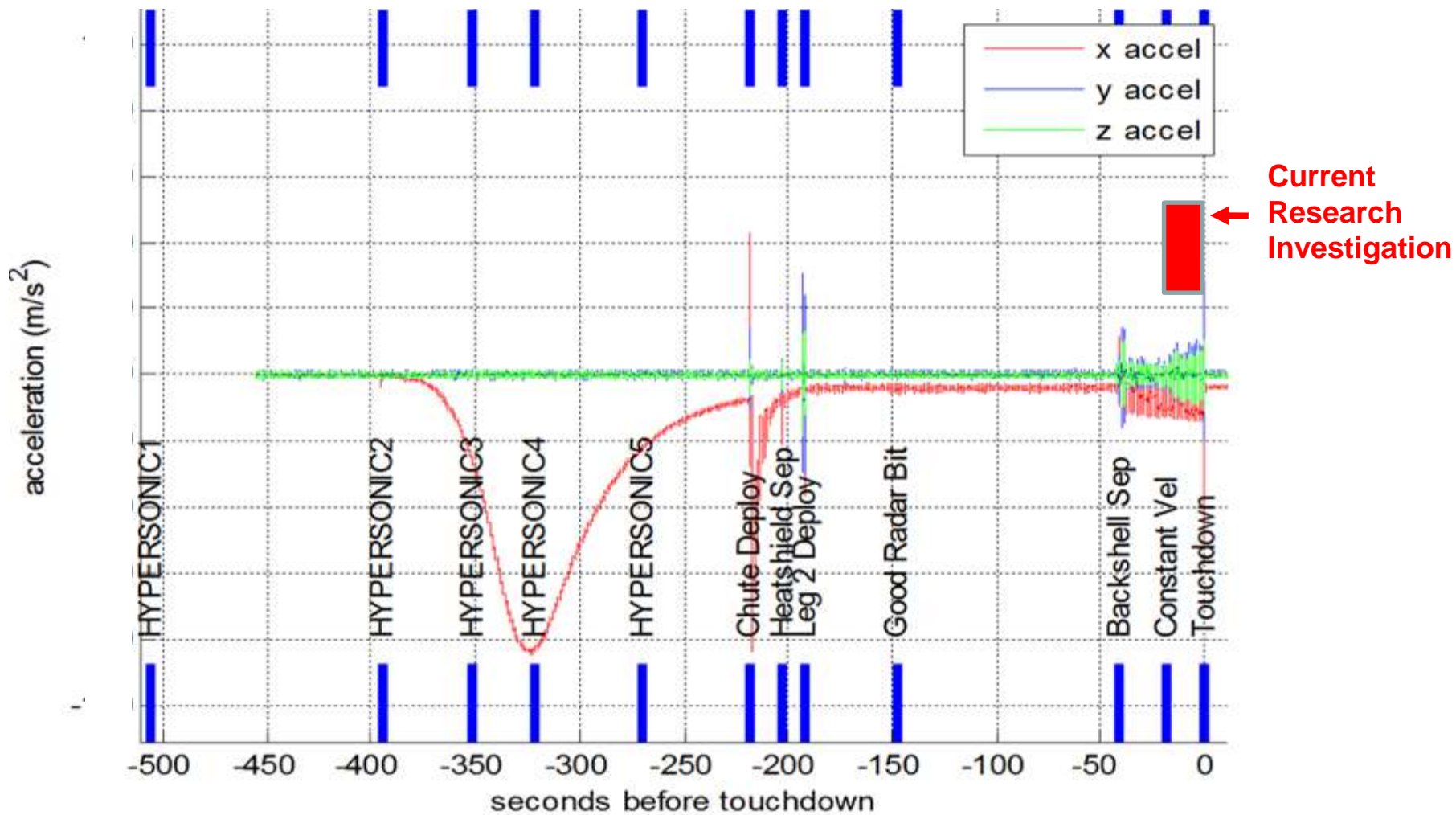
$P_c \sim 1200$ kPa
0 deg cant
 $h/d_e = 25$
Steady-state
 N_2 test gas

FLUENT



Phoenix Entry, Descent and Landing Sequence

-200 Hz (Inertial Measurement Unit) IMU data and 10 Hz Radar data



Viscous Shear Erosion

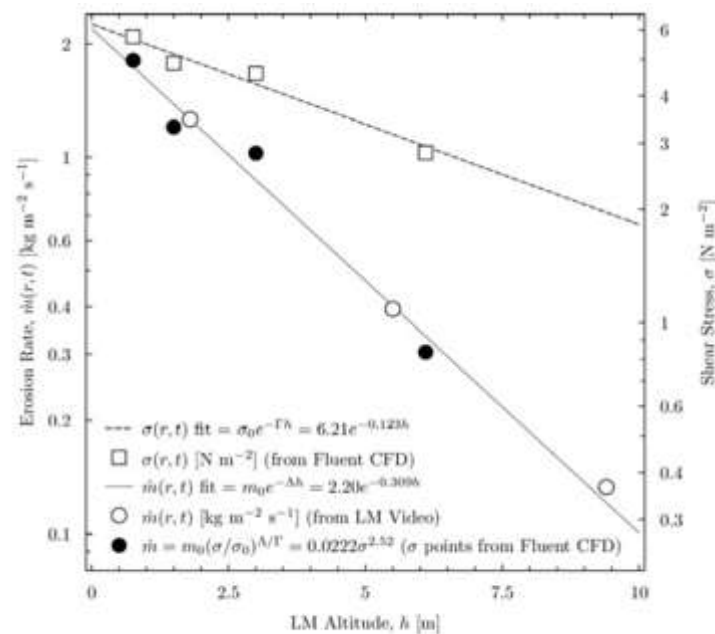
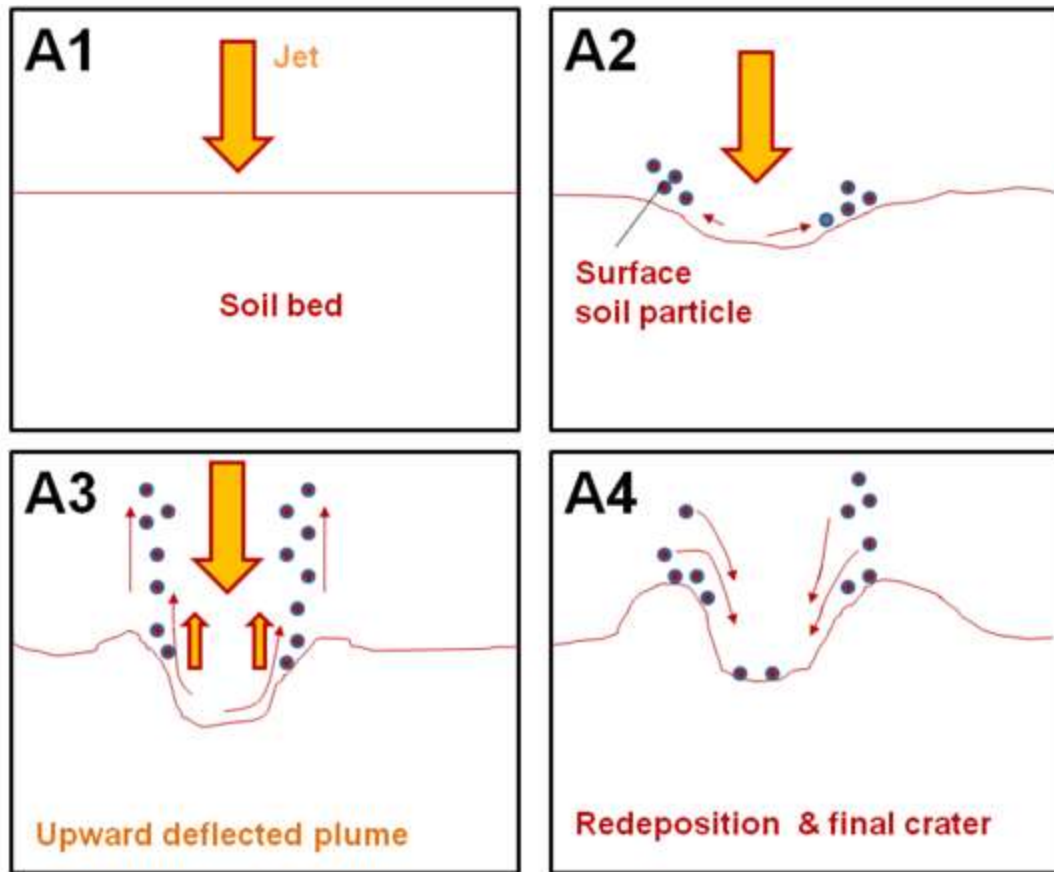
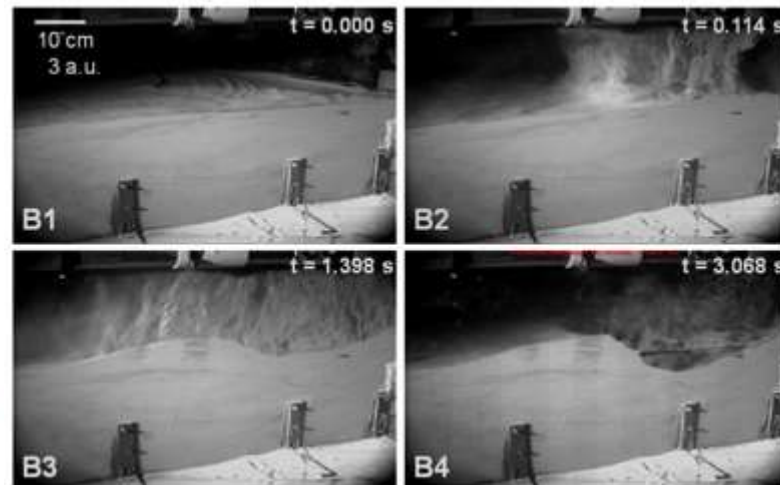
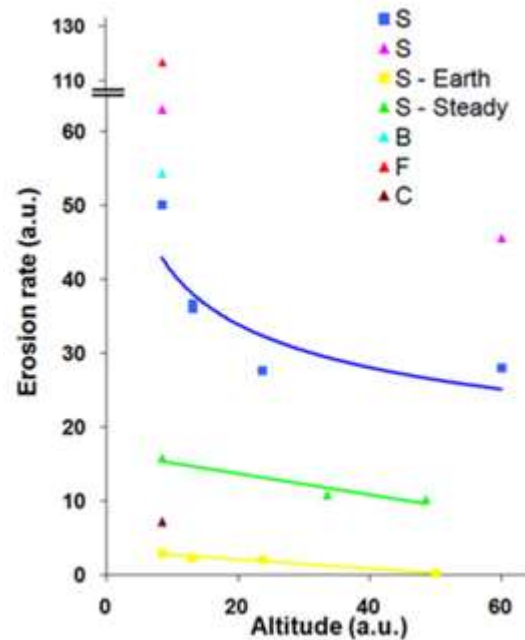
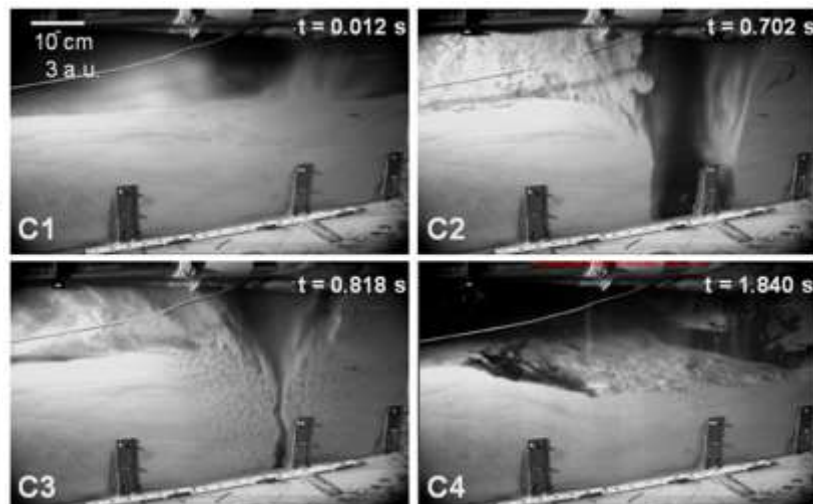
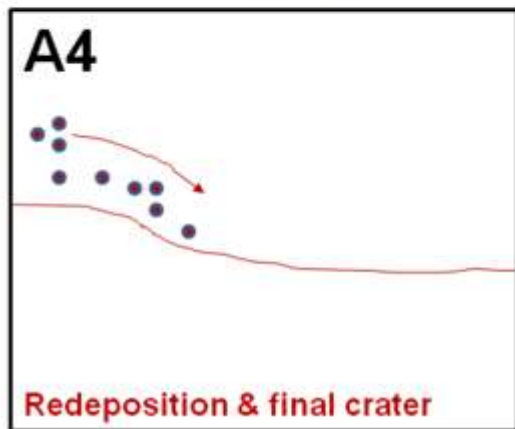
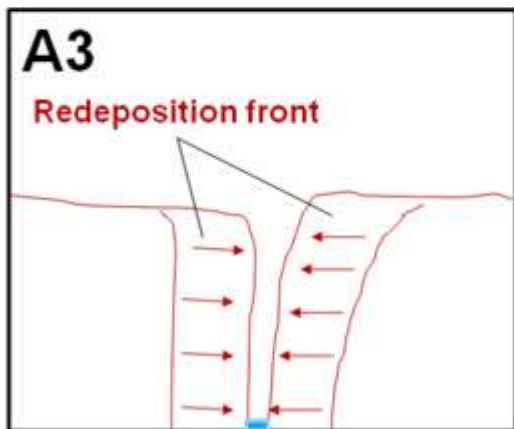
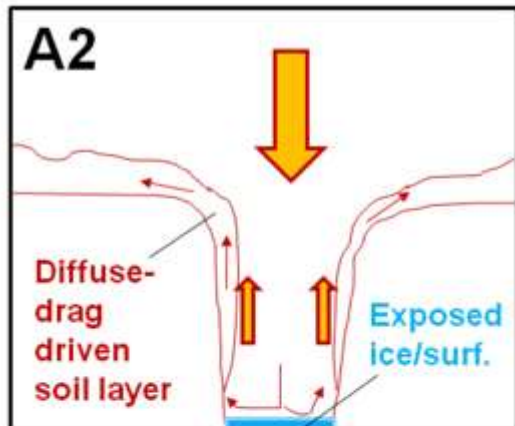
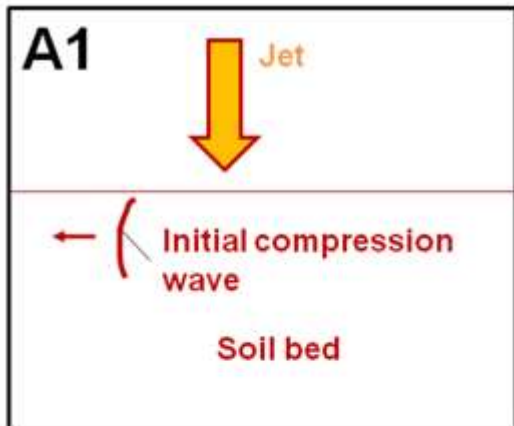


Fig. 11. Averaged shear stress and mass erosion rate as a function of $h(t)$.

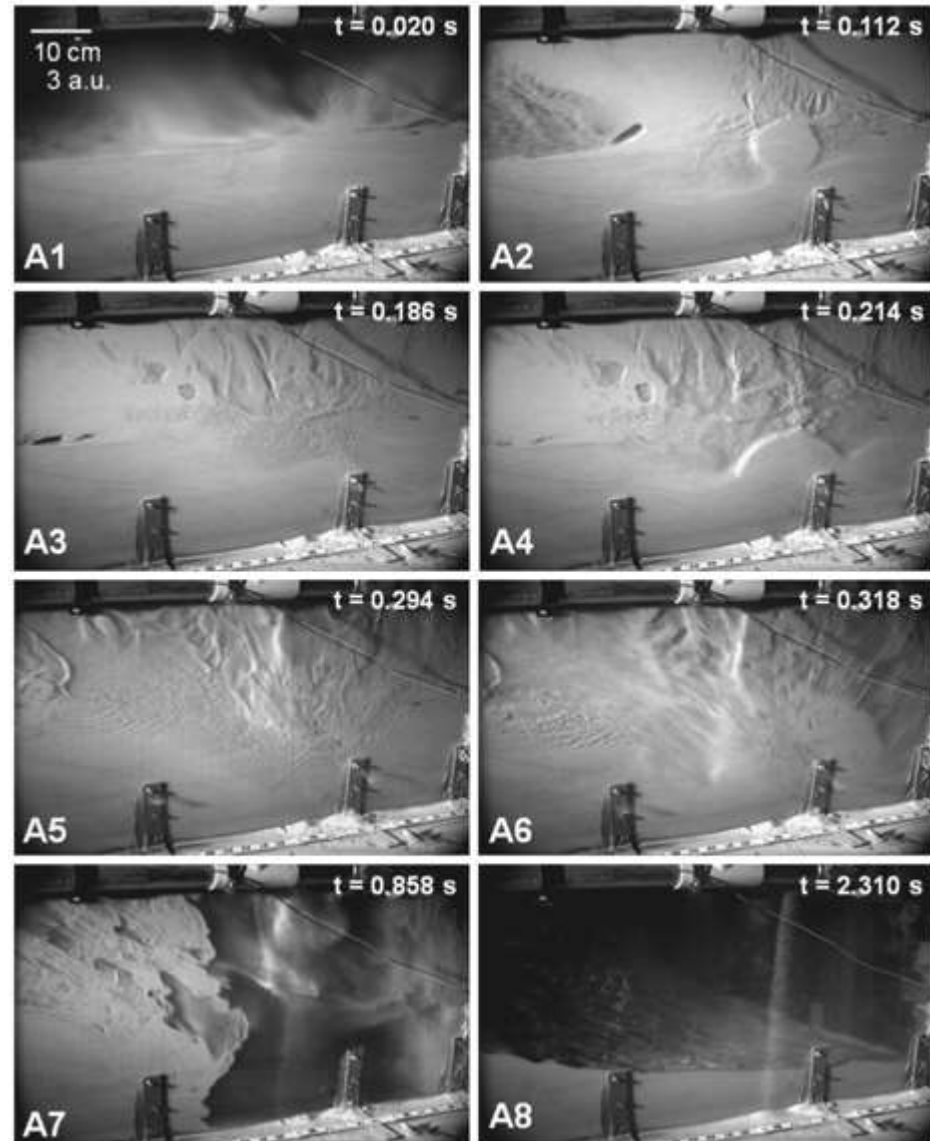
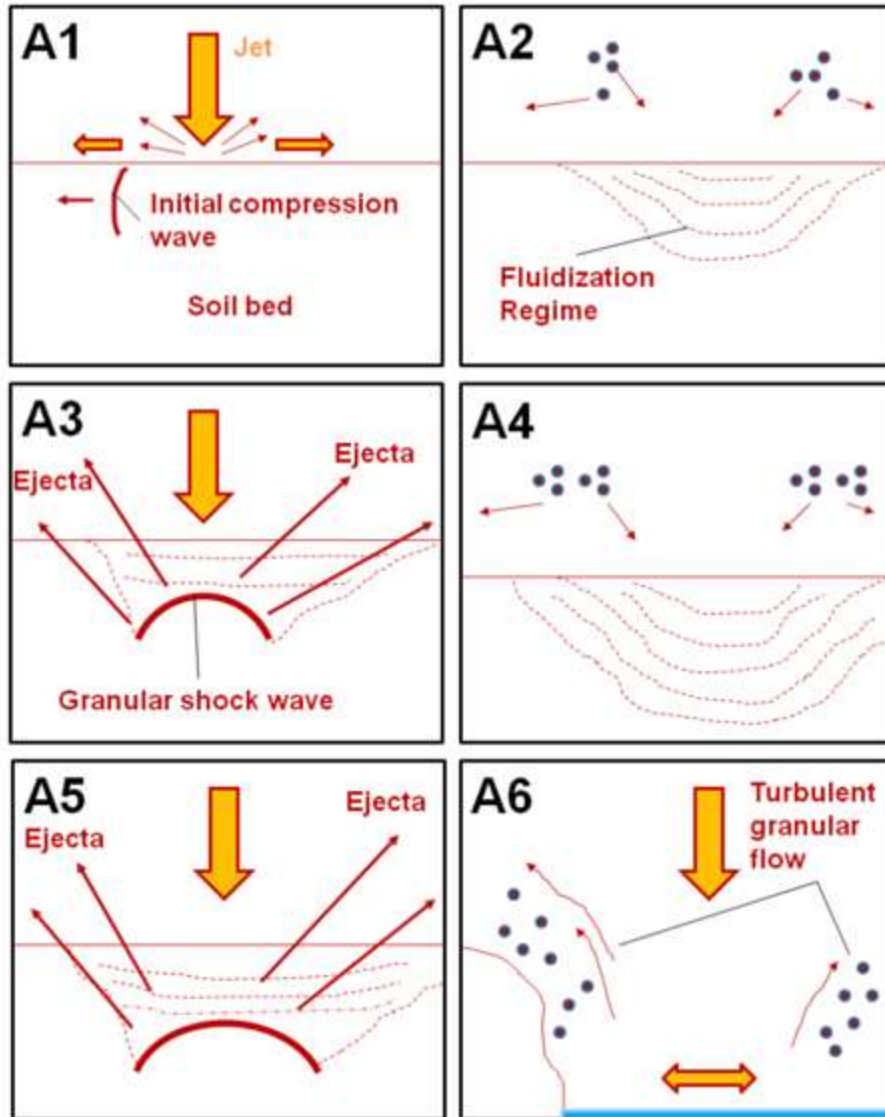


Bearing Capacity Failure





Explosive Erosion





PSI Ground Test Data Gaps

Rocket Engine	Thrust	Pambient	Pc (psia)	Propellant	Area Ratio	Scale	Date	Test Obj
Surveyor Vernier (JPL-Northrop)	20 lbf	1e-4 Torr	?	Hydrazine	86	Full-Scale	1967	Erosion Study
Hydrazine Monoprop (JPL-LaRC)	607 lbf	5.2 Torr	?	Hydrazine	20	Sub-Scale	1971	Erosion Study
Viking Descent Engine 18-nozzle (NASA - Lockheed)	150 lbf	11 Torr	67	Hydrazine	20	Full-Scale	1973	Erosion Study
24-nozzle engine (NASA - Lockheed)	150 lbf	11 Torr	91	Hydrazine	20	Full-Scale	1973	Erosion Study
Fluted nozzle (NASA - Lockheed)	153 lbf	11 Torr	73	Hydrazine	20	Full-Scale	1973	Erosion Study
LM retrorocket (LaRC)	100 lbf	2e-4 Torr	?	Hydrazine	?	Sub-Scale	1968	Erosion Study
Modified Surveyor Vernier (LaRC)	61 lbf - 32 lbf	0.02 Torr	155 - 80	Methyl-Hydrazine/NO	20	Full-Scale	1969	Erosion Study
Modified Mariner mid-course correction motor (LaRC)	37 lbf - 10 lbf	0.02 Torr	147 - 43	Hydrazine	20	Full-Scale	1969	Erosion Study
NASA Human-Class Lander Rocket Engine	25000 - 5000 lbf	10 Torr	?	CH4/LOX	?	Full-Scale	TBD	Erosion Study
SpaceX Red Dragon Rocket Engine	5000 lbf	10 Torr	?	Methyl-Hydrazine/N2O	3.84	Full-Scale	TBD	Erosion Study

- Limited full-scale hot-fire tests have been conducted to evaluate the plume-induced site-alteration hazards
- **These test programs were an order of magnitude smaller in engine thrust than the lunar/Mars cargo/human-class landing engine requirements (> 5000 lbf)**
 - **Cannot extrapolate erosion & ejecta data from small science lander engine ground tests**
- No full-scale hot-fire plume-soil erosion test program for a human-class lunar and/or Mars lander has been conducted to date
- Do not recommend running cold gas jets for developing any plume-induced design environment database for landers. Cannot simulate plume density, viscosity, velocity and shear layer physics to flight which are all first-order effects for multi-plume and multi-phase surface interactions. This often results in more questions than answers...

Lack of high fidelity plume-induced erosion ground test for cargo/human-class Mars/lunar landers increases mission risk during the landing phase and prevent development of design environments



PSI Ground Test (GT) Gaps and KPPs

- All ground tests will be with jet impingement on lunar/Mars geotechnical simulant and flat surface
- **Gap 1: Lack of controlled hot-fire flight-scale thrust environments (addressed by GT KPP 2)**
 - Cold flow testing does not simulate plume physics, erosion physics and granular flow mixing
 - Cold flow does not simulate plume density, viscosity, velocity and shear layer physics
 - Cannot extrapolate erosion/ejecta predictions based on thrust without data-based scaling correlations
 - Increasing thrust leads to differences in erosion physics
 - Granular dynamics does not scale with geometric length
- **Gap 2: Lack of reduced ambient pressure environments representative of the lunar/Mars atmosphere (addressed by GT KPP 3)**
 - Cannot adequately simulate plume physics and ground pressure distributions, necessary for adequately simulating the erosion physics and ejecta dynamics
- **Gap 3: Lack of testing with dynamic descent profiles representative of landing systems (addressed by GT KPP 1)**
 - Static testing does not adequately simulate plume physics and effects on regolith
 - Relatively slow engine start-up may simulate effect of dynamic descent
- **Gap 4: Lack of non-intrusive testing (addressed by GT Diagnostics & FI KPPs)**
 - Non-intrusive test techniques and diagnostics needed to adequately capture the data
- **None of the tests in the past have addressed the combination of these technical GT gaps to satisfy project goals**
 - Requires innovative test facility, test hardware and diagnostic development and modifications
 - None of these tests are run-of-the mill standard NASA practices
 - Requires advancement in the SOA to obtain high fidelity relevant data sets
- **GT KPPs developed to tangibly address these four technical PSI GT gaps**

<u>KPP1: Simulated PSI Landing Descent Profile^A</u>	0 m/s (static)	0 m/s to 1 m/s*	0 m/s to 2 m/s**
<u>GT KPP 2: PSI Landing Thrust Environments^A</u>	50 N to 700 N (intrusive, cold gas, sub-scale)	50 N to 10,000 N (intrusive & non-intrusive, cold gas, hot flow, sub-scale, flight-	50 N to 30,000 N (non-intrusive, hot flow, flight-scale)
<u>GT KPP 3: PSI Landing Ambient Pressure Environments^A</u>	10 ⁵ Pa to 1,000 Pa	10 ⁵ Pa to 500 Pa	10 ⁵ Pa to 50 Pa

A – To test landing environments with granular media and a flat plate for targeted thrust profiles and ambient pressures. Focus on reduced ambient pressure conditions.



GT Goal 1: Relevant and Non-Intrusive Environment Needs

◆ Definition of relevant environment

◆ Needed to satisfy all PSI goals

◆ Satisfy most of the relevant parameters for 3 out of the 4 proposed GTs

Parameters	Relevant	Non-Relevant	Priority	Notes
Jet Temperature	Hot	Cold	1	Critical to match state and transport properties and gas-granular mixing
Jet Composition	Rocket Plume Species	Air, N ₂ , He	2	Critical to match transport properties and gas-granular mixing
Jet Thrust	300 N to 30,000 N (Flight-Scale)	< 50 N (Sub-Scale)	1	Critical to match ground pressure distribution, erosion regime and vary thrust over a large range to obtain scaling correlations
Atmospheric Pressure	<10 ³ Pa	10 ⁵ Pa (Earth SL)	1	Critical to match plume expansion, ground pressure distribution & erosion regime and vary over a large range to obtain scaling correlations
Regolith Shape	Irregular	Spherical	1	1st order effect on erosion physics and ejecta dynamics
Regolith Size Distribution	Polydisperse	Monodisperse	1	1st order effect on erosion physics and ejecta dynamics
Regolith Bulk Density	600 kg/m ³ to 1900 kg/m ³	1900 kg/m ³	1	1st order effect on erosion physics and ejecta dynamics and critical to vary to obtain scaling correlations
Descent Profile	Dynamic	Static	2	1st order effect on erosion physics, but can we correct for it?
Atmospheric Composition	CO ₂ /Near Vacuum	Air	3	Unknown effect

Non-Intrusive

Intrusive

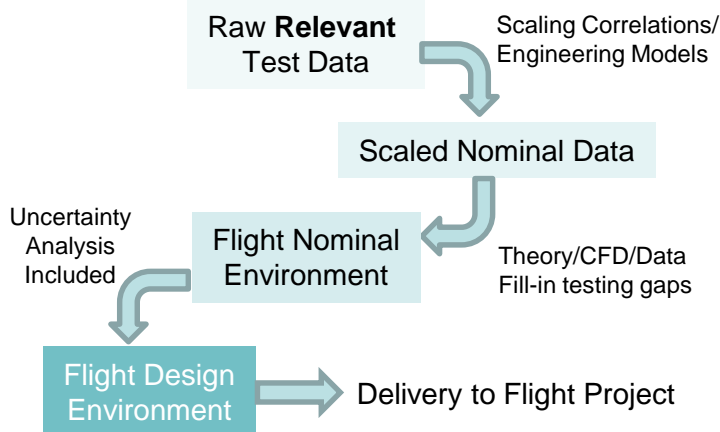


- Need non-intrusive tests to generate scaling correlation based engineering models for predicting flight environments and to qualify flight instrumentation
- Not needed for pure computational validation



GT Goal 2: Data-Driven Engineering Predictions

- Generate flight design environment predictions from **relevant** test data and scaling correlations independent of computational sims
 - *SLS EM-1*: Approach taken for ascent and in-space design environment predictions in aerothermodynamics, aeroacoustics and aerodynamics
 - *SLS EM-1*: Test data driven and computational solutions fill in the data gaps
- Generate scaling correlations as a function of nondimensional parameters that account for thrust, plume expansion, gravity, plume transport and soil properties
 - *SLS EM-1*: Matched important non-dimensional parameters and minimized scaling
 - *Historical Launch Vehicles*: Scaling correlation engineering models show good agreement with flight data
 - Need to run sensitivity studies over large ranges within the non-dimensional parameters to obtain adequate engineering models
 - Important PSI non-dimensional parameters developed through multi-phase flow theory



Development of SLS base convective heating flight design environment

$$\text{Plume Physics} = f\left(Ma, Re_j, \frac{P_e}{P_\infty}, \gamma, \frac{T_e}{T_w}, Kn\right)$$

$$\text{Erosion Physics} = f\left(C_T, Fr_d, \frac{U_{*t}}{U_*}, \frac{Y_s}{\tau_w}, Da\right)$$

$$\left(Da = \frac{kP_j}{\mu L}, C_T = \frac{T}{qA}, Fr_d = \frac{U_j}{\sqrt{\frac{\rho_s}{\rho_j} g \bar{d}_s}}\right)$$

$$\text{Ejecta Dynamics} = f\left(C_d, Re_s, Fr_d, \frac{U_s}{U_j}, \beta, Stk\right)$$

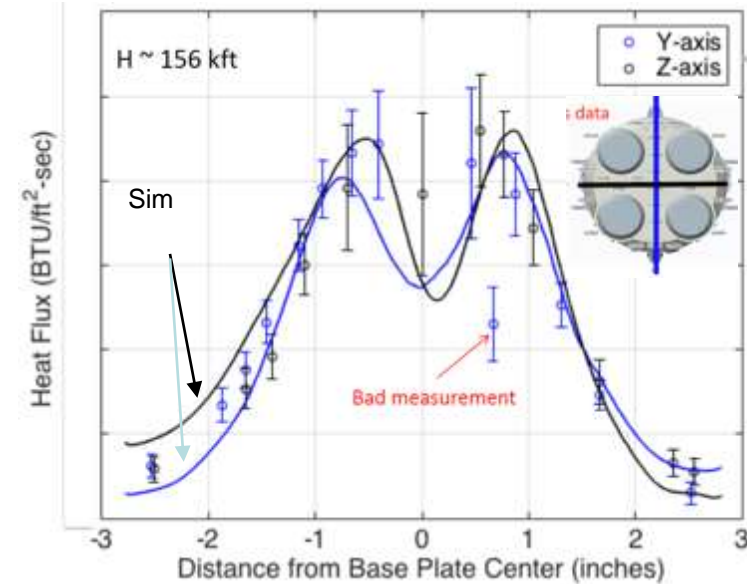
$$\left(\beta = \frac{\rho_s d_s}{C_d}, Stk = \frac{\rho_s d_s^1 U_j}{18\mu_j}\right)$$

PSI non-dimensional parameters to address 3 sub-disciplines

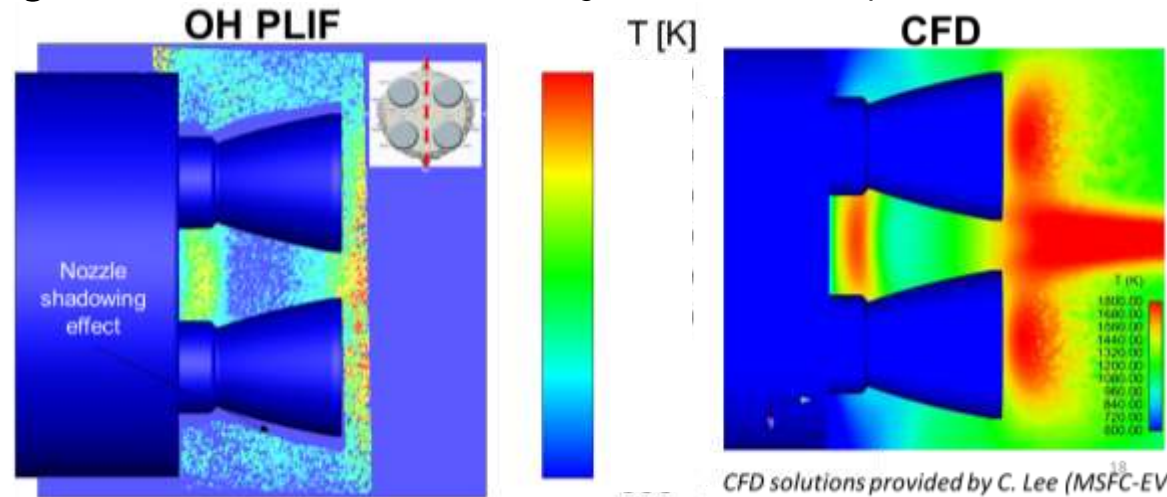


GT Goal 3: Computational Model Validation + Advancement

- ◆ Compare relevant GT data to computational simulations to improve model development and increase code TRL
- ◆ Goals to compare between GT data and computational sim are: (1) plume shock structure, (2) ground pressure distribution, (3) transient and mean erosion profiles and rates, (4) ejecta velocities, concentration and flux and (5) lander heating and pressure environments
- ◆ All GTs are focused on this goal



SLS base heating distribution comparisons between relevant ground test and computational sim



SLS gas temperature distribution comparisons between relevant ground test and computational sim

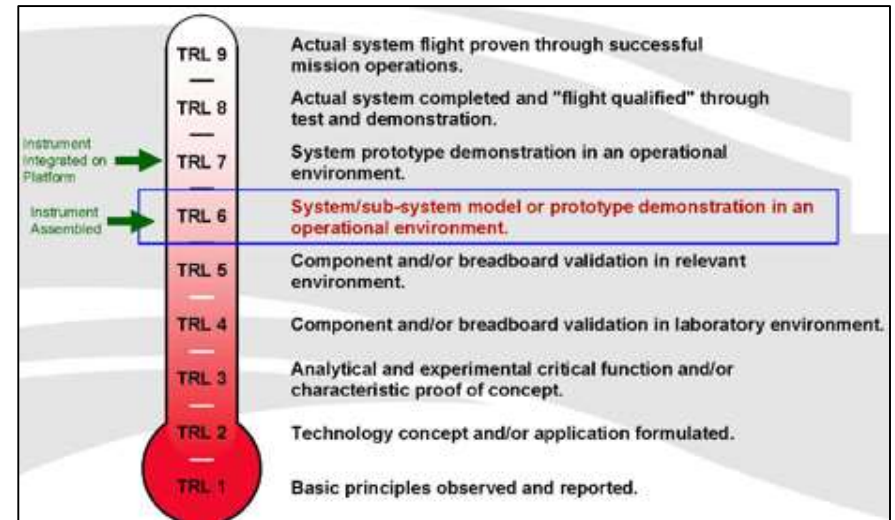


GT Goal 4: Flight Instrumentation in Relevant Environments + Conclusions

◆ Proposed flight instrument testing in relevant environments

◆ Leads to a final instrument TRL between 5 and 8

- Able to reduce feasibility and technical risks to flight qualify
- Able to reduce cost and schedule risks when flight project funds completion of instrumentation



Flight Instrument TRL

Conclusions - GT KPPs were developed for the following reasons:

- Mitigate technical gaps within PSI GTs (similar to the computational front)
- Tangible advancement in the SOA (different from ESM)
 - None of the MSFC, GRC & LaRC GTs are standard NASA practices (different from ESM)
 - Requires innovation on multiple fronts to obtain relevant and non-intrusive environments
- GT data set stand-alone products to assist in 3 fundamental areas (different from ESM):
 - Flight design environment and engineering model development
 - Computational model improvement + advancement and validation
 - Flight instrumentation qualification
- Harsh Lessons Learned of past and non-relevant PSI data sets
 - JPL and JSC mistrust of past PSI data sets based on past reviews for Altair, Phoenix and MSL Missions
 - Comparison of non-relevant environment data sets to computational sims decreases code TRL
 - Reduces flight instrumentation TRL



GT Diagnostics/Instrumentation Needs

ARC GT	MSFC GT	GRC GT	LaRC GT	Parameter	Notes				
Cold Gas w/Regolith & Flat Plate	Hot-Fire w/Regolith & Flat Plate*	Hot-Fire w/Regolith & Flat Plate*	Hot-Fire/Cold Gas w/Flat Plate	Test Type	*Able to also test with cold gas as needed by computational group				
Sub-scale	Sub-scale/Science Lander FLT Scale	Exploration Lander FLT Scale	Sub-scale	Scale					
0 to 60	0 to 48	0 to 36	TBD	H/De	H = Altitude; De = Nozzle Exit Diameter				
GN2/GAir	GH2/LCH4/LOX *	LCH4/LOX	GH2/GOX	Propellants	*MSFC GT can operate with LOX/LCH4 or LOX/GH2				
<50 lbf	50 lbf to 400 lbf *	1500 lbf to 5700 lbf	100 lbf to 400 lbf	Thrust	Advancing the SOA from ARC to GRC GTs * Need to determine thruster size based on facility performance				
0.08 psi to 14.7 psi	0.02 psi to 14.7 psi*	0.02 psi to 14.7 psi	0.02 psi to 14.7 psi	Ambient Pressure	*MSFC GT can achieve lower ambient pressure than 0.02 psi dependent on thruster size				
0 ft/s (static)	0 ft/s to 3.3 ft/s (dynamic, const rate)	0 ft/s to 6.6 ft/s (dynamic, const rate)	0 ft/s (static)	Descent Velocity	Advancing the SOA from ARC to GRC GTs				
End of FY20	Mid FY21	Mid FY22	Mid FY23	Completed Year					
ARC GT	MSFC GT	GRC GT	LaRC GT	Parameter	Uncertainty	Parameter	Uncertainty	Parameter	Uncertainty
Surveying	Surveying	Surveying	N/A	Erosion Rate	10%	Erosion Dimmensions	10%		
N/A	SCALPSS/stereo	SCALPSS/stereo	N/A	Erosion Rate	2%+	Erosion Dimmensions	2%+		
1/2 Space Exp	N/A	N/A	N/A	Erosion Rate		Erosion Dimmensions			
N/A	mm-wave Radar	mm-wave Radar	N/A	Ejecta velocity	TBD	Erosion rate			
Optical Diag	Optical Diag	N/A	N/A	Ejecta velocity	5%				
N/A	LLIRDI Prototype	LLIRDI EDU	N/A	Plume Structure	25%	Blast Zone Deposition	TBD		
Some instrumentation (press only)	LLBI	LLBI	Some form of base instrumentation	Base pressure/heat transfer	5%				
Instr. Plate (press only)	Instr. Plate	Instr. Plate	Instr. Plate	Impingement pressure/heat transfer	5%				
Optical Extinction	Optical Extinction	Optical Extinction	N/A	Ejecta bulk density	12%	Erosion rate	TBD		
Aerogel	Aerogel	Aerogel	N/A	Ejecta energy flux	30%	Ejecta particle flux	20%	Erosion Rate	33%
N/A	SALT	SALT	N/A	Ejecta energy flux	10%	Ejecta particle flux	10%	Erosion Rate	15%
N/A	OM	OM	N/A	Particle Size Distr	10%				
N/A	IR	IR	IR	Plume Structure	25%				
NO PLIF	OH PLIF	N/A	OH PLIF	Plume Structure	10%	Plume Temp	12%	Plume Velocity	TBD
BOS/Schlieren	BOS/Schlieren	BOS	BOS/Schlieren	Plume Structure	TBD	Plume Density	TBD		
Direct Shear	Direct Shear	Direct Shear	N/A	Shear Strength	10%	Cohesion	25%	Friction Angle	5%
Penetrometer	Penetrometer	Penetrometer	N/A	Compressive Strength	10%	Compaction	TBD		
Sieve Analysis	Sieve Analysis	Sieve Analysis	N/A	Particle Size Distr	8%				
Photoanalysis	Photoanalysis	Photoanalysis	N/A	Particle Size Distr	10%				
Plenum	Thruster Instr	Engine Instr	Thruster Instr	Eng. Pc	5%	m-dot	TBD		
	Proposed instrument critical								
	Proposing instrument funding in FY21 GCD Call								
	Proposed instrument ideal but not critical								



Ground Testing

- ◆ ARC-GT1: Subscale lander configuration cold flow test with flat plate/regolith at the ASU/ARC Planetary Aeolian Lab (140,000 ft³ vacuum chamber): base/plate instrumentation, Schlieren, stereo crater imaging, measuring ejecta dynamics (MSFC, ARC, KSC)



Plume Flow Physics
Ejecta Dynamics
Cratering Physics
Diagnostic Development

- ◆ MSFC-GT2: Subscale hot-fire test (<400 lb_f thrust LOX/LH₂ or LOX/LCH₄ MET1 thruster) with flat plate/regolith at the MSFC Test Stand 300 Vacuum Chamber (3,200 ft³): IR imaging, base/plate instrumentation, stereo crater imaging, measuring ejecta dynamics, dust density (MSFC, KSC, LARC)



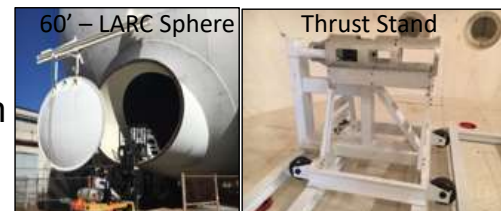
Plume Flow Physics
Ejecta Dynamics
Cratering Physics
Diagnostic Development
FLT Instrument Qual

- ◆ GRC-FLT-Scale GT (GT3): Flight-scale hot-fire test (7,500 lb_f thrust LOX/LH₂ or LOX/LCH₄ AMPed engine) with flat plate/regolith and dynamic test stand at GRC In-Space Propulsion Facility (260,000 ft³ vacuum chamber): IR imaging, base/plate instrumentation, stereo crater imaging, measuring ejecta dynamics, dust density (GRC, MSFC, KSC, LARC)



Plume Flow Physics
Ejecta Dynamics
Cratering Physics
FLT Instrument Qual

- ◆ LARC-GT4: Subscale lander configuration cold flow/hot-fire test (4x100 lb_f thrust LOX/LH₂ thrusters) with normal/inclined flat plate at the LARC 60' Vacuum Sphere (113,000 ft³): OH/NO PLIF, base/plate instrumentation, IR, Schlieren, PSP (LARC, MSFC)



Plume Flow Physics
Diagnostic Dev



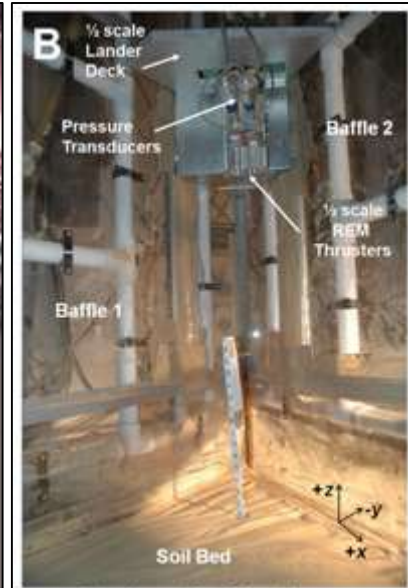
Ground Test 1 (GT1)

- Design, fabricate and integrate MSFC Cold Gas 100 lbf thruster lander configuration within the ARC Planetary Aeolian Laboratory (PAL)
 - 141,000 ft³ chamber (60 feet high)
 - Cold N₂ line
 - Integrate 4 thrusters in a conceptual simplified lander configuration
 - Thruster fabricated by ER and ET10
- Acquire and integrate KSC soil bin within PAL
 - Acquire < 5 mT of BP-1 (sorted for ~100 um) and two other types of regolith of varying particle density
- Conduct 10 tests with an instrumented flat plate
- Conduct 40 tests with regolith
 - BP-1 and lower density particles
- Diagnostics
 - Stereo camera to visualize the crater morphology, erosion rates during descent and determine dust density (leverage SCALPSS if available)
 - IR imager to visualize the rocket plume interactions (increase TRL) if available
 - mm-wave Radar to measure ejecta velocity and trajectory (increase TRL) if available
 - Optical diagnostics to track particles and gas flow visualization
 - Instrumentation to determine impingement and base pressures (increase TRL)
- Plan is to conduct 50 cold flow tests for ~3 second at different static altitudes on a bed of regolith at ambient pressures from 14.7 psia to 0.05 psi.
 - Run various sensitivity studies of thrust, altitude, ambient pressure and soil properties

PAL



Thruster – Soil Bed



- Measurements
 - Flow visualization, base pressure, erosion rate, ejecta velocity, dust cloud density, crater dimension and volume



Ground Test 2 (GT2)

MSFC Test Stand 300 15' Vac Chamber

- Acquire and integrate MSFC ER LOX/LH2 or LOX/LCH4 400 lbf thrust rocket engine (MET1) within MSFC Test Stand 300 Vacuum Chamber Facility
 - Acquire Dewars from CDA
 - Engine can be integrated easily with TS300
 - LOX and LH2 cyrolines already exist
 - Leverage LRE from GT1
- Fabricate static test stand for TS300
 - MSFC ET10 and ET50 lead this effort
- Acquire and integrate KSC soil bin within TS300
 - Acquire < 5 mT of BP-1 (sorted for ~100 um) and two other types of regolith of varying particle density
 - KSC to design, fabricate and ship soil bin to TS300
- Conduct 5 tests with an instrumented flat plate
- Conduct 25 tests with regolith
 - BP-1 and lower density particles
- Diagnostics
 - Stereo camera to visualize the crater morphology, erosion rates during descent and determine dust density (leverage SCALPSS)
 - IR imager to visualize the rocket plume interactions (increase TRL)
 - mm-wave Radar to measure ejecta velocity and trajectory (increase TRL)
 - Optical diagnostics to track particles and gas flow visualization
 - Instrumentation to determine impingement and base pressures and heating rates (increase TRL)
- Plan is to conduct 25 hot-fire tests for ~2 second at different static altitudes on a bed of regolith at ambient pressures from 14.7 to 0.05 psi.
 - Run various sensitivity studies of thrust, altitude, ambient pressure and soil properties



MSFC ER LOX/LH2 <700 lbf Engine



- Measurements
 - Flow visualization, base pressure & convective heat rates, erosion rate, ejecta velocity, dust cloud density, crater dimension and volume
- Goal for computational code validation and engineering model development



Flight-Scale Integrated Ground Test (GT3)

- ◆ Acquire and integrate MSFC ER LOX/LH2 or LOX/LCH4 7,500 lbf rocket engine (AMPed) within GRC Plum Brook In-Space Propulsion Facility (ISP)
 - Completed design and development of the injectors, thrust chamber and nozzle (some components fabricated using additive manufacturing)
 - Component testing and performance plan to be completed
 - Prop valves and cryogenic tanks are currently in development and will be completed prior to FY22
 - Leverage lander engine by MSFC Lander Office (no cost to acquire engineering unit for this test program)
- ◆ Design and fabricate dynamic test stand and integrate within ISP
 - MSFC ET10 lead this effort
 - Conduct sea-level testing of the ER engine and test stand
 - If dynamic test stand incurs large technical risks, develop a static test stand with adjustable heights
- ◆ Acquire and integrate KSC soil bin within ISP
 - Acquire < 15 mT of BP-1 (sorted for ~100 um)
 - Plan is to leverage soil bin developed for GT1 if possible
- ◆ Conduct a 5 tests with an instrumented flat plate
- ◆ Conduct 25 tests with regolith
 - BP-1 and lower density particles
- ◆ Diagnostics
 - Stereo camera to visualize the crater morphology, erosion rates during descent and determine dust density (leverage SCALPSS)
 - IR imager to visualize the rocket plume interactions (increase TRL)
 - mm-wave Radar to measure ejecta velocity and trajectory (increase TRL)
 - Optical diagnostics to track particles and gas flow visualization (leverage FY19 CIF)
 - Instrumentation to determine impingement and base pressures and heating rates (increase TRL and leverage impingement plate from GT1)
- ◆ Plan is to conduct 25 hot-fire tests for ~6 second duration with engine descending on a bed of regolith at ambient pressure from 14.7 psia to 0.1 psi.

MSFC Lander Engine



GRC ISP



- Measurements
 - Flow visualization, base pressure & convective heat rates, erosion rate, ejecta velocity, dust cloud density, crater dimension and volume
- **Gold Standard Test Program**
 - Minimized scaling
 - All parameters match closely to flight and only need to account for low gravitational effects which can be scaled through running various particle densities
 - Able to almost directly scale this data to flight and develop design environments (**first of its kind**)
 - Critical to compare computational codes to this data set



Ground Test 4 (GT4)

- Design, fabricate and integrate MSFC cold gas/hot-fire 400 lbf thrust sub-scale lander configuration within the LARC 60'-Sphere
 - Integrate 4x100 lbf cold gas and LOX/LH2 thrusters in a conceptual simplified lander configuration
 - Thruster to operate as cold gas and rocket engine
 - Leverage WSTF/LARC thrust stand
 - Leverage thruster fabricated for GT2
 - Leverage lander configuration developed for GT1
- Acquire instrumented impingement plate from GT2
- Conduct 30 tests with an instrumented flat plate
 - Plate to be positioned normal and inclined to the plume flow
- Diagnostics
 - Background oriented Schlieren (BOS)
 - OH/NO PLIF
 - Pressure-Sensitive Paint (PSP)
 - Instrumentation to measure impingement and base pressures and heating rates (increase TRL if LLBI developed in time)
- Plan is to conduct 50 cold flow tests for ~3 second at different static altitudes on a bed of regolith at ambient pressures from 14.7 psia to 0.05 psi.
 - Run various sensitivity studies of thrust, altitude, ambient pressure and soil properties

60' – LARC Sphere



Thrust Stand



- Measurements
 - Flow visualization, plume velocity and temperature, lander base and impingement pressure and convective heating rate measurements



PSI Flight Data Gaps

- ◆ **Viking:** Virtually no flight data captured of the eroded site
- ◆ **Pathfinder:** Air-bags – no plume-surface interaction data collected
- ◆ **MER:** Air-bags - no plume-surface interaction data collected
- ◆ **Surveyor 3:** Quantified the sand-blasting of its' panels by the Apollo 12 landing, but no 3D erosion data captured
- ◆ **Surveyor 6:** “Hop test” to determine effects of thrust on jet-induced erosion and soil properties, detailed images obtained but no pseudo-stereo or stereo imaging acquired to accurately reconstruct the eroded site
- ◆ **Phoenix:** Limited flight data captured at post-landing, but not able to adequately reconstruct due to non-stereo or non-pseudo-stereo images obtained
- ◆ **Apollo:** Limited flight data obtained through uncalibrated imagery and astronaut notes, heavy ejecta and onset observed and pre-landing terrain not adequately assessed, difficult to quantify erosion rates and surface morphology due to large uncertainties

No data
High uncertainties
Large assumptions

- ◆ **InSight:** Post-landing high quality pseudo-stereo flight data captured and high fidelity 3D reconstruction developed from the Instrument Deployed Camera, no erosion onset, pre-landing topography or soil properties captured which leads to uncertainties
- ◆ **MSL:** Post-landing high quality stereo flight data captured and high fidelity 3D reconstruction developed from the Mastcam, provided surface erosion onset landing video but no pre-landing topography which leads to uncertainties

Moderate/high
uncertainties
Large assumptions

The development of PSI flight data has been mostly ignored for the last 60 years



PSI Flight Data Needs

◆ Flight Data Needs:

- Transient erosion profiles and erosion rates
 - Final erosion profiles and mean erosion rates as backup option
- Plume structure such as plume expansion angle, stand-off shock distance and diameter
- Altitude of erosion onset
- Pre-landing topography of the landing site
- Ejecta density, velocity and energy flux
- Landing site regolith properties (cohesion, particle size distribution, bulk density)
- Telemetry
- Engine Performance (Thrust, mass flow rates, chamber pressure and temperature and geometry)

Most current flight data of plume-surface interactions are not able to validate complex numerical models and/or engineering models.



FI KPPs

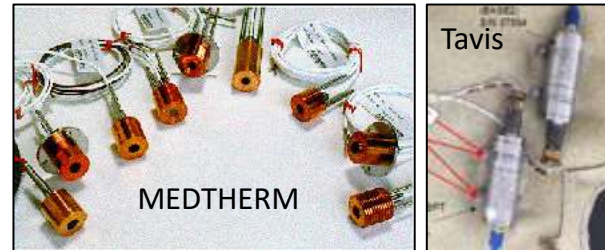
Key Performance Parameters: PSI Prototype Flight Instruments

Parameter		State of the Art	Threshold Value	Project Goal
KPP 1: Particle velocity measurement		N/A*	Measurement uncertainty of +/- 25% for particle sizes 50 to 200 micron**	Measurement uncertainty of +/-10% for particle sizes from 5 to 400 micron***
FI KPP 2: Vehicle base instrumentation	Surface Pressure wrt Engine Thrust	N/A*	Measurement uncertainty of +/-25% for engine thrust levels from 50 N to 10,000 N up to Mars ambient pressure**	Measurement uncertainty of +/-10% for engine thrust levels from 50 N to 30,000 N up to near-Lunar ambient pressure**
	Surface Heating wrt Engine Thrust	N/A*	Measurement uncertainty of +/- 25% for engine thrust levels from 50 N to 10,000 N up to Mars ambient pressure**	Measurement uncertainty of +/- 10% for engine thrusts from 50 N to 30,000 N up to near-Lunar ambient pressure**
FI KPP 3: Plume structure and blast zone measurements		N/A*	Plume structure measurement uncertainty of +/- 25% wrt the nozzle**	Plume structure and blast zone diameter measurement uncertainty of +/- 10% wrt the nozzle***



PSI Flight Instrumentation Development

- ◆ LLBI: Integrate and flight qualify lander base pressure and heat flux gauges (heritage instrumentation) to measure landing plume aerothermal and aerodynamic effects (MSFC, LARC)



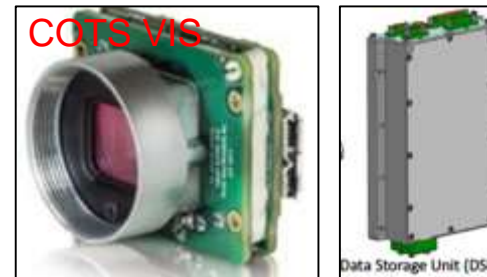
Plume Flow Physics
FLT Instrument Qual

- ◆ LLIRDI: Develop and flight qualify IR imager to visualize rocket plume interaction effects and hot ejecta deposition/dynamics (MSFC)



Plume Flow Physics
Ejecta Dynamics
FLT Instrument Qual

- ◆ SCALPSS: Flight qualify lander visible stereo camera through PSI GTs to measure crater morphology and ejecta/dust density during descent (LARC, MSFC). Funded through SMD NPLP.



Ejecta Dynamics
Cratering Physics
FLT Instrument Qual

- ◆ mm-wave Radar: Flight qualify mm-wave radar instrument through PSI GTs to measure ejecta velocity, particle sizes and mass flux (KSC, MSFC).



Ejecta Dynamics
FLT Instrument Qual



SCALPSS



SCALPSS
Stereo CAmeras for Lunar Plume-Surface Studies

SCALPSS is a NASA-Provided Lunar Payload (NPLP)

Payload Objective

- Collect validation data for plume-surface interaction analysis, critical for future Lunar and Mars lander vehicle designs, supporting SKG III-D

Payload Overview

- Capture stereo images from the time of plume impingement on the lunar surface, through touchdown and after engine shutoff
- Return critical data about the onset, rate, shape and volume of plume crater formation, to support model validation

Approach

- Purchase 4 each (TBR) off-the-shelf cameras and assemble 1 Data Storage Unit (DSU)
- Compare Mars 2020 to Lunar lander environments and perform delta-qualification testing
- Deliver to Lander provider for integration; support test and ops
- Perform Crater analysis after data is returned to Earth, document and publish

Team Roles / Responsibilities

- Lead: LaRC (Earth Science, test, MEDLI, MEDLI-2 experience)
- Co-I: MSFC (camera design, photogrammetry and CFD analysis)
- Consultant: JPL Mars 2020 camera lead

Key Dates / Programmatics

- ATP: February 21, 2019
- Project Categorization Agreement (LaRC/NPLP): April 12, 2019
- Project Initiation: 22 May, 2019
- CLPS Lander announced: May 30, 2019
- Hardware Delivery: March 31, 2020
- Data Analysis Complete, Landing + 3 months (TBD)

Cost

- \$1.45M, full-cost (operations support and data analysis not included)

Leverages Mars 2020 Downlook Camera and SLS Onboard Imaging System

Camera:

- FLIR CM3-03-13Y3C-CS
- 47mm x 38mm x 46mm

Lens:

- Universe Kogaku DC-95JP

Data Storage Unit (DSU):

- 99mm x 140mm x 30mm

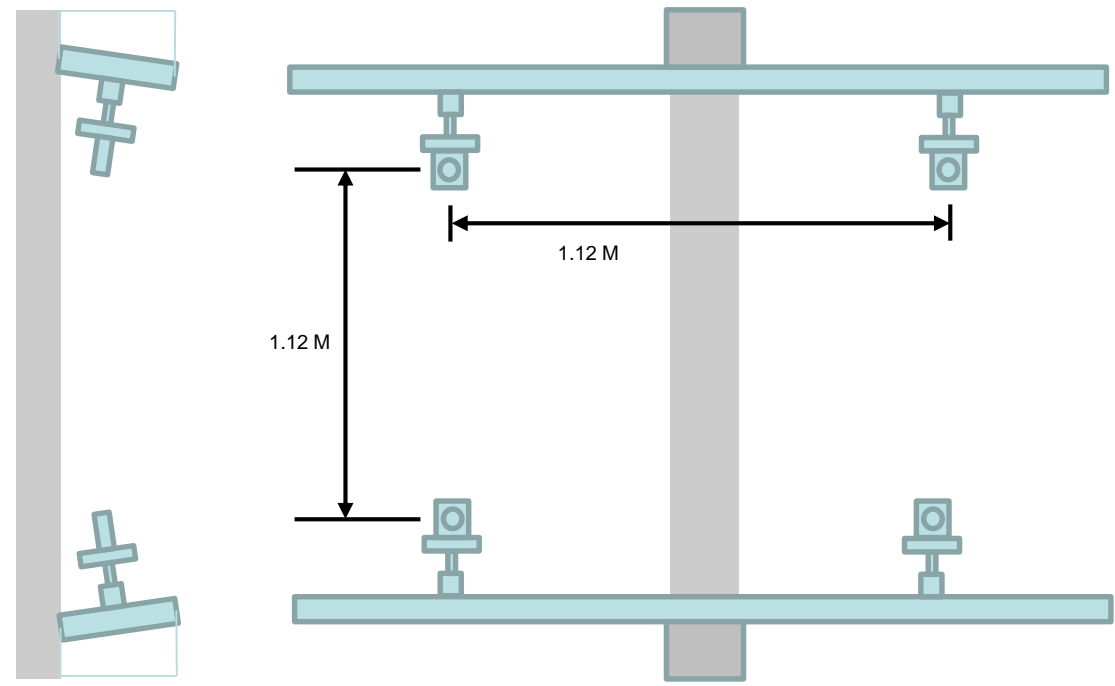






Peau Productions
3.37 mm fl lens

FLIR Camera Models
 13Y3C – 1280 x 1024 Color
 31S4C – 2048 x 1536 Color
 31S4M – 2048 x 1536 Monochrome





Plume-Surface Interaction (PSI) 3D Reconstruction

◆ Stereo-models generated using:

- Radial distortion models provided by InSight Instrument Deployed Camera, IDC (Justin Maki)
- XYZ & quaternions provided by InSight IDC (Rob Grover)
- Ground control points (GCPs) provided by LM high-fidelity CAD (Mark Johnson)
- 8 non-stereo images taken from the PSI dedicated IDC imaging campaign (InSight Surface Ops)
 - Camera's XYZ location and rotation matrix changed from image to image creating pseudo-stereo pairs
 - Led to more challenges and uncertainty in generating stereo-models

◆ Surface mapping

- Import stereo-models
- Map points and lines on the surface
- Generate Digital Terrain Map (DTM)
- Output volumes and dimensions

◆ Accuracy/uncertainty quantification

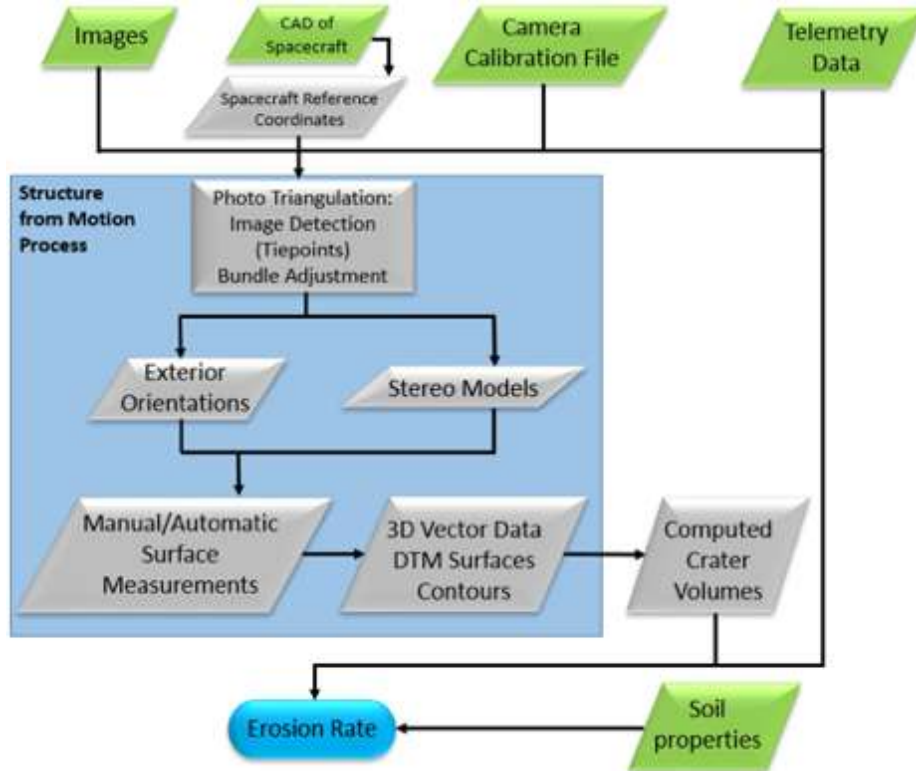
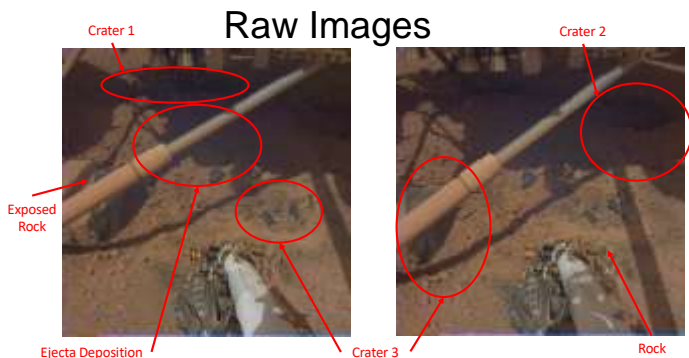


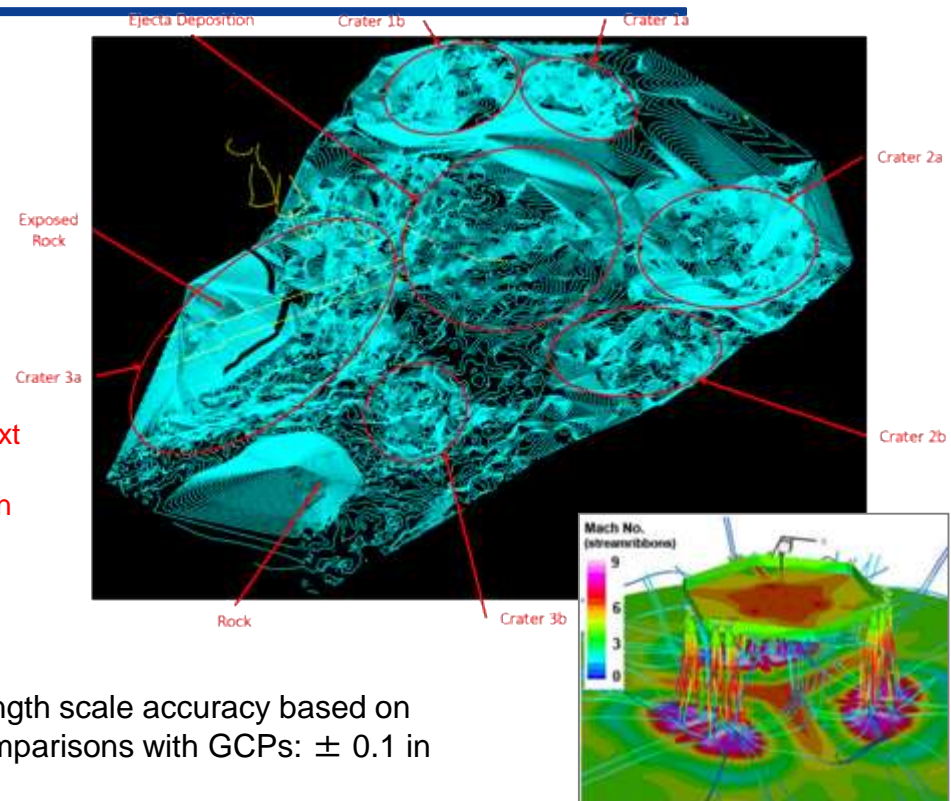
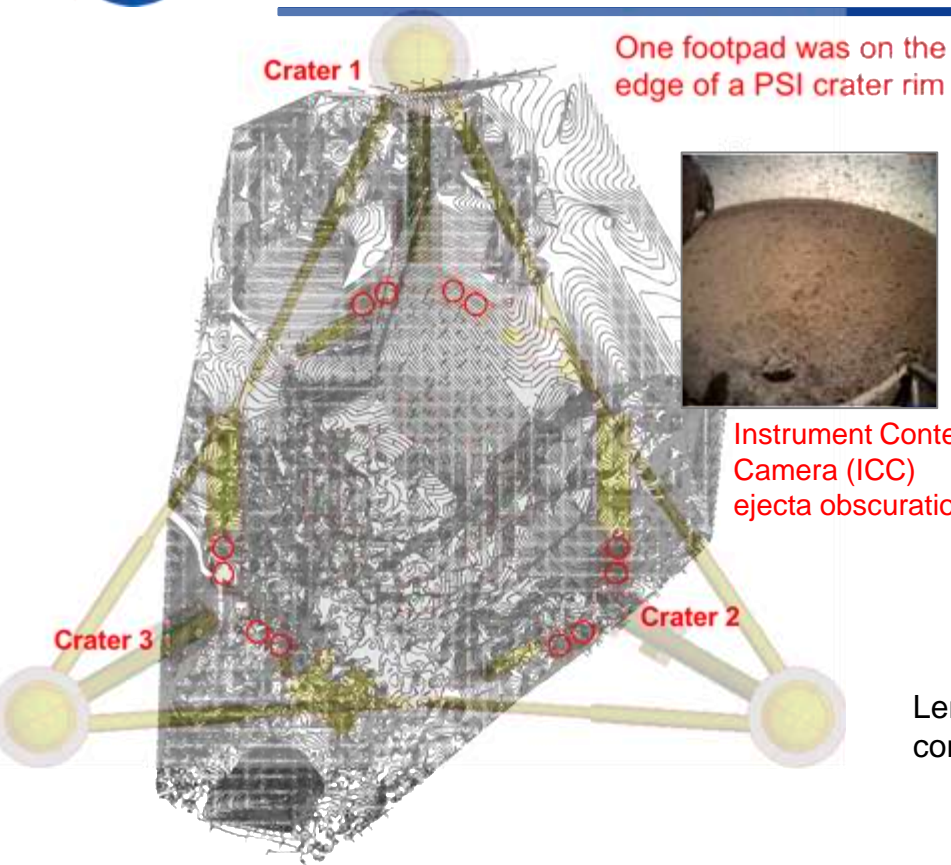
Image Processing
Photogrammetry



- DTM
- Crater Volume
- Erosion Rates

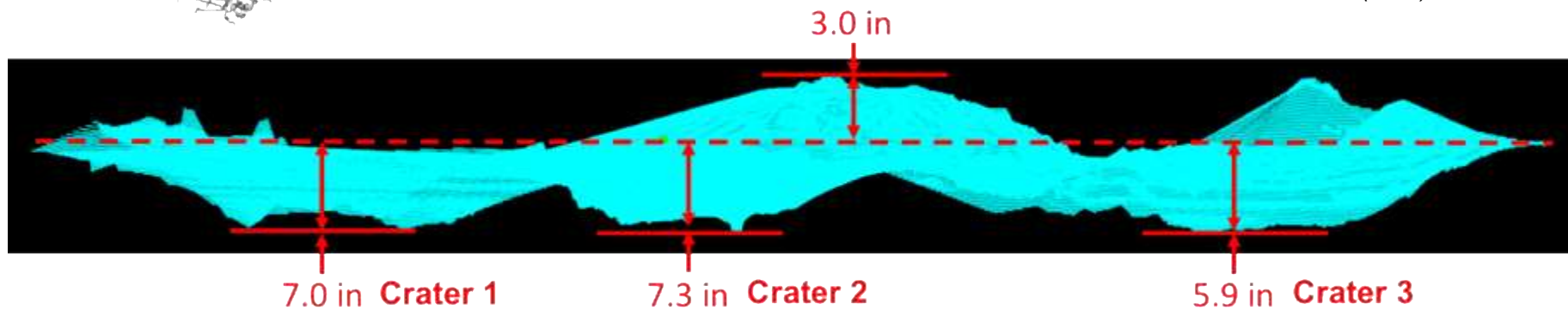


PSI Site-Alteration DTM



Length scale accuracy based on comparisons with GCPs: ± 0.1 in

Gulick (2006), Lockheed Martin





Observations & Conclusions

Lander	Crater	Max Depth	Average Diameter	Eroded Volume	Average Erosion Rate	Peak Thrust
InSight	Crater 1	6.97 in	20.1 in	2203 in ³	55.1 lb _m /s	270 lb _f
	Crater 2	7.28 in	21.1 in	1902 in ³	47.6 lb _m /s	
	Crater 3	5.91 in	22.7 in	1809 in ³	45.3 lb _m /s	
MSL	Goulburn	2.64 in	52.4 in	665 in ³	2.0 lb _m /s	371 lb _f
	Burnside	2.01 in	68.5 in	3283 in ³	10.0 lb _m /s	
	Hepburn	2.87 in	78.7 in	3881 in ³	11.7 lb _m /s	
	Sleepy Dragon	4.02 in	88.2 in	5167 in ³	15.7 lb _m /s	

- Three large PSI craters observed
 - Two sub-craters per engine cluster supports ground pressure distributions from CFD
- Average InSight PSI crater diameter 21 inches and 7 inches deep
- Assume flat pre-landing terrain (agrees with photogrammetry results and surface ground points)
- InSight observed the deepest site alteration of all Mars landing missions to date due to:
 - Pulse-modulated engines
 - Loose and deep regolith landing site requirement
- InSight PSI erosion rate 5x that of MSL
 - Assuming InSight & MSL drift-mixed soil bulk density similar to Phoenix (Shaw *et al*, 2009)
- Footpad on Crater 1 rim
 - Could have led to a ~5° lander tilt if footpad settled within Crater 1
- Ejecta from craters impinged on the lander base and deposited in the center
 - Large ejecta flux could have damaged lander base instrumentation and led to significant ejecta obscuration on the ICC
- Can be used to qualitatively assess PSI effects for M2020 and MSR

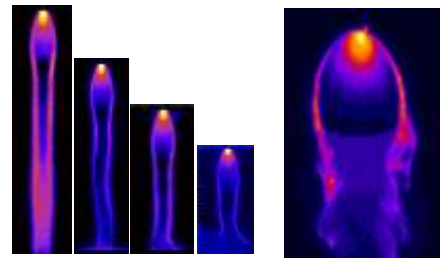


Predictive Simulation Capability Tasks

Completion of the PSC tasks will be greatly enhance physics modeling

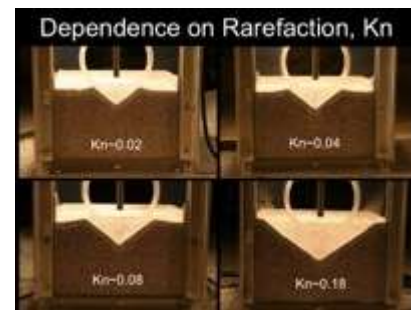
◆ PSC Task 1 – Plume Flow in Low Pressure Environment

- Lunar vacuum and Mars low pressure environments require mixed continuum-rarefied flow simulation capabilities. Production CFD code has mixed rarefied flow solver capability implemented; however, it has not been validated. Research code needs rarefied solver implemented
- Plume simulations validated against existing data and PSI GT data



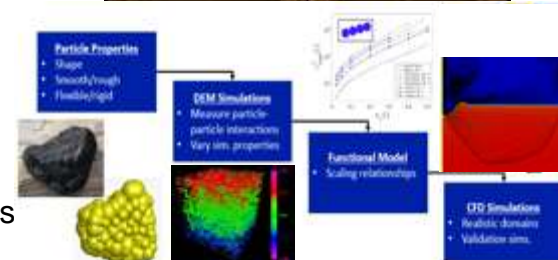
◆ PSC Task 2 - Effect of Mix Continuum/Rarefied Flow on Crater Development and Ejecta Sheets

- Strong dependence of plume induced crater size on flow rarefaction effects. Shows first order effect on ejecta streams and crater size/shape formation for lunar environment.
- Prediction simulation tools will be enhanced and validated against the existing data and GT data. Functional and validated mix continuum/rarefied PSI simulation capability that accurately captures crater formation and ejecta transport.



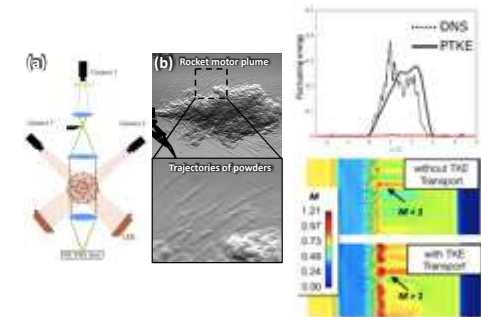
• PSC Task 3 – Regolith Particle Phase Modeling

- Regolith particle phase modeling requires resolving complexities particular to extraterrestrial regolith surface material composition. Erosion process and crater shape for Lunar regolith demonstrated to be strongly driven by two factors: irregular particle shapes and poly-disperse particle size mixture.
- In this task, particle phase models will be implemented into predictive simulation tools and matured. Predictive simulation tools will be validated against processing and analyzed data in PSC Task 2 and proposed ground test data.



• PSC Task 4 - Gas – Particle Interaction Modeling

- Large uncertainties exist gas particle interactions models implemented in current simulation tools. The suitability and accuracy of incompressible modeling formulations on modeling the compressible plume induced erosion must be addressed. A model for gas particle cloud kinetics has been identified as not existing. Accurate gas particle interaction modeling is required for lunar environments and will be implemented through unit physics experiments and development of gas-particle interaction models.





Collaborations with DLR

- ◆ **Develop high-fidelity ground based diagnostics to investigate PSI**
 - Ejecta particle velocity, acceleration and trajectories
 - Ejecta bulk density
 - Ejecta gas velocity
 - Erosion rates
 - Transient crater profiles

- ◆ **Accurate plume computational modeling (continuum regime)**
 - Single engine and multi-engine configurations
 - Unsteady impingement flow data sets (heating and pressure)
 - Plume interactions with landing struts and lander base (heating rates and pressure)
 - Plume inviscid flow and stagnation structures

- ◆ **Validating codes with wind tunnel test data**

- ◆ **Develop a unit experiment that looks at rocket plume shear layer effects on a cylinder**

- ◆ **Brainstorming of other areas PSI related**