A SUITE OF TOOLS FOR PREDICTIVE SIMULATION OF PLUME SURFACE INTERACTIONS

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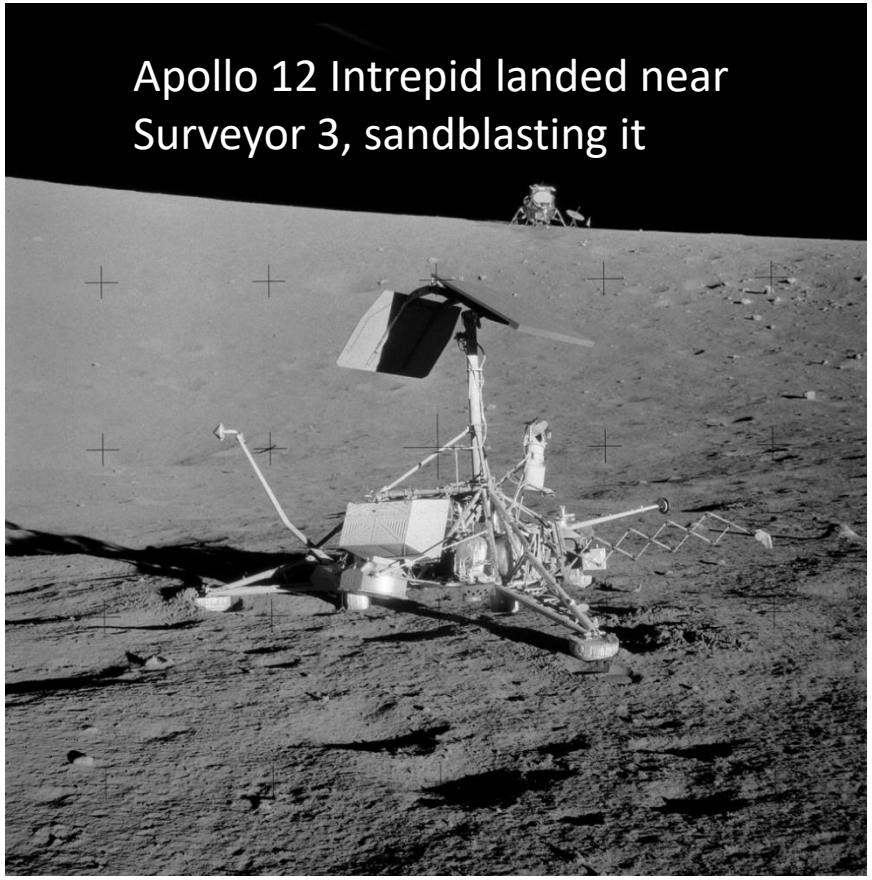
Introduction

- Plume Surface Interaction (PSI) involves complex physics, including plume alteration, cratering, and ejecta that have the potential to drive mission success / failure
- Several lunar 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)
- NASA is returning to the moon 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

Programs and projects including HLS, CLPS, SCALPSS, HLS providers, Gateway, Habitat, Pressurized Rover, and other science missions and elements require PSI environment predictions now to assess risk and make design decisions

Driving Need/Pull for Tool Suite

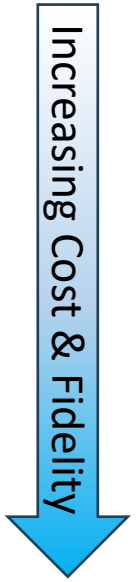




Predictive Tool Suite

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

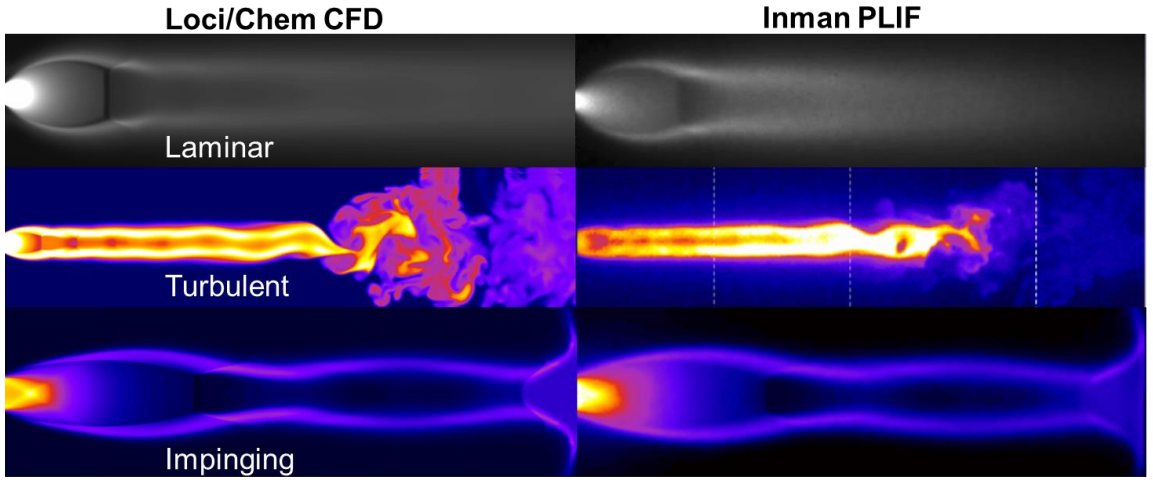
- NASA Marshall Space Flight Center's propulsion fluid dynamics branch actively maintains, matures, and uses a suite of tools (with varying fidelity and computational cost) for predicting PSI effects



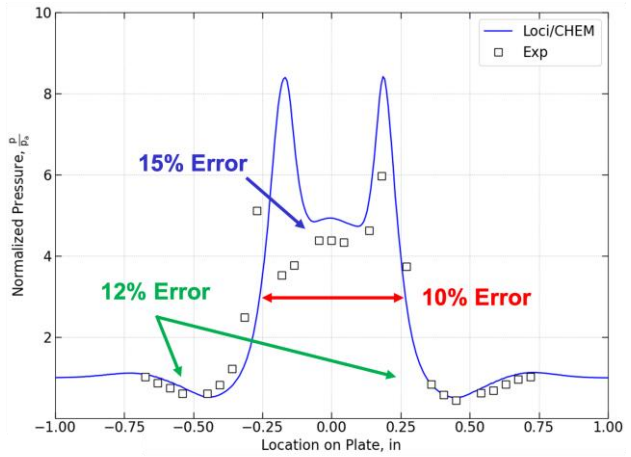
- Loci/CHEM Navier-Stokes solver with chemical reaction capability
- Loci/CHEM-Boltzmann mixed regime solver for continuum and rarified flows
- Debris Transport Analysis (DTA) tool for evaluating ejecta particle trajectories
- Descent Interpolated Gas Granular Erosion Model (DIGGEM) – Engineering model of crater formation which requires fixed altitude CFD or test results as inputs
- Loci/CHEM-DIGGEM – Hybrid CFD/Engineering model simulates gas phase and models crater formation due to viscous shear erosion (VSE) from impinging plume
- Gas Granular Flow Solver (GGFS) – High fidelity multi-phase tool that directly simulates regolith interacting with rocket plume gas for all erosion regimes

Loci/CHEM

- Loci/CHEM is a density-based, Navier Stokes CFD tool capable of modeling:
  - 3D geometry
  - Subsonic/supersonic flow
  - Steady/unsteady flow
  - Reacting/non-reacting flow
  - Laminar/turbulent flow
- Primary PSI metrics include impingement pressure, shear stress, heat flux, and forces & moments



Comparison of impinging plume between Loci/CHEM (left) and experimental Planar Laser Induced Fluorescence (right)



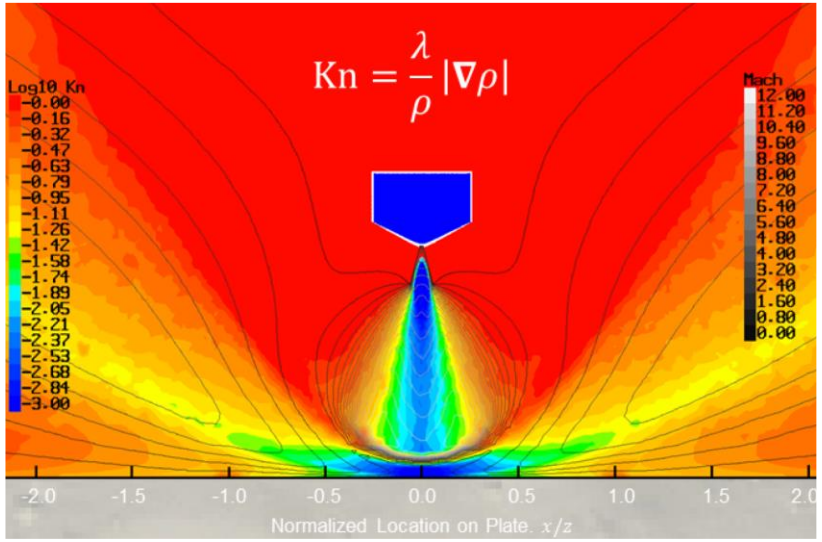
Impingement Pressure Comparison for Impinging Plume Shown at Left

- Loci/CHEM is a validated tool for predicting plume flowfield, impingement pressures and shear stresses from continuum and into transition regime
  - Shock structure metrics within 5%
  - Plume impingement pressure/shear stress typically within ~10-15% (>50% for Kn>0.3)

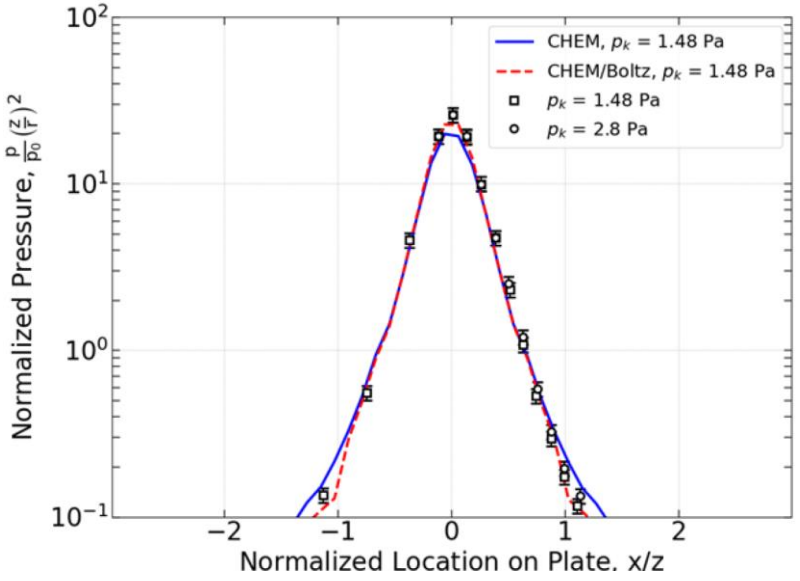
Loci/CHEM-Boltzmann

- Loci/CHEM-Boltzmann is a mixed continuum/rarified solver that extends ability to model plume flows in very low pressure/density environments
- Numerically solves Navier-Stokes equations in low Knudsen number regions, and Boltzmann equation in high Knudsen number (rarefied) regions
- Primary metrics are plume impingement pressure, shear stress, and heat flux
- Has been validated for rarefied impinging plumes against a data set from 1988 H. Legge experiment
  - Predicts shear stress in rarified regions within 10%

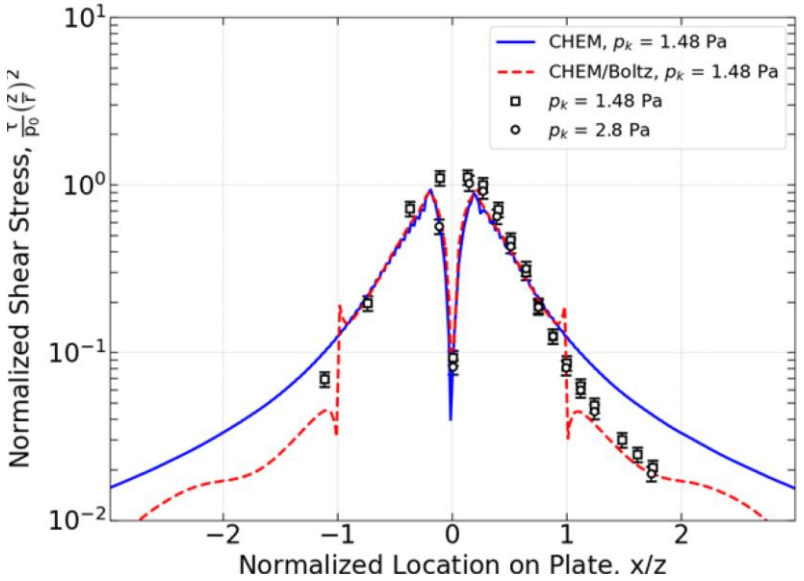
Knudsen number for normally impinging plume from 1988 Legge experiment as simulated with Loci/CHEM-Boltzmann



Both Loci/CHEM and Loci/CHEM-Boltzmann correctly calculate impingement pressure distribution

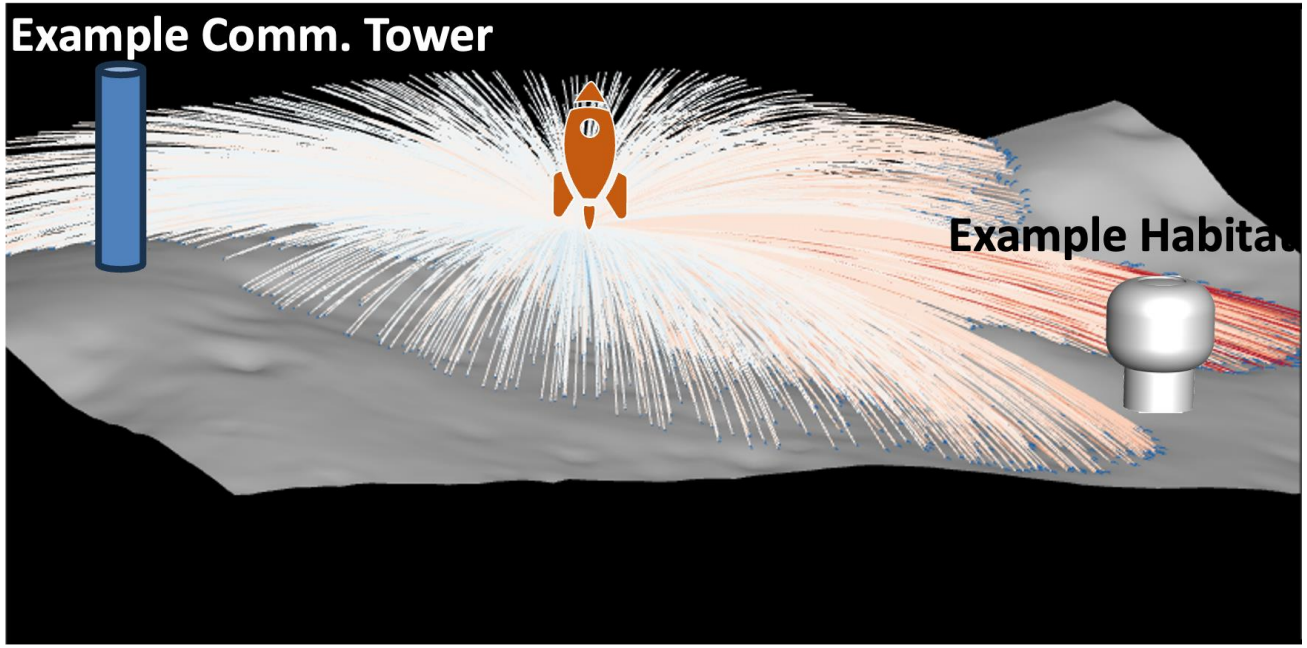


Loci-CHEM-Boltzmann produces correct shear stress beneath low density portion of radial wall jet where Loci-CHEM alone overpredicts

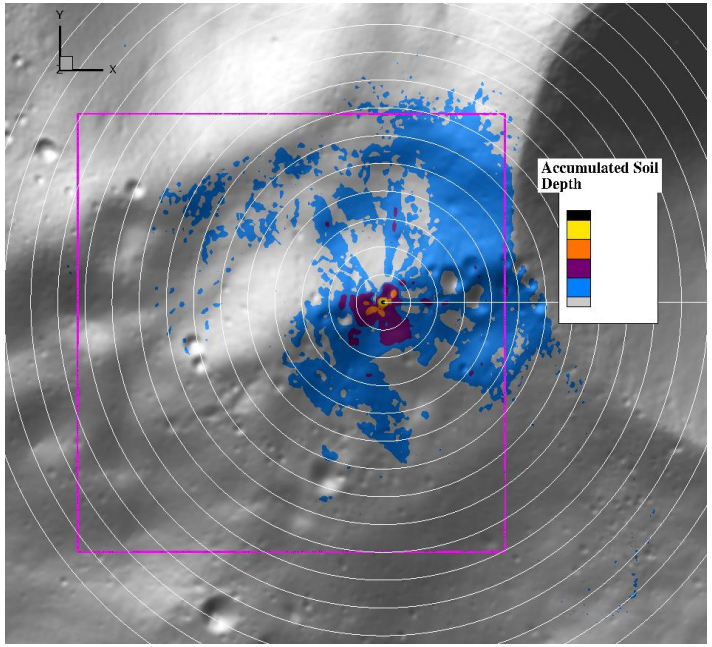


Debris Transport Analysis (DTA) Tool

- The DTA Tool allows 1 way coupled calculation of particle trajectories using CFD (Loci-CHEM, Loci/CHEM-Boltzman, etc) generated flow fields and drag models which are valid for a wide range of Reynolds, Mach, and Knudsen numbers
- Has been extensively verified, validated, and used for STS and SLS lift-off debris



Example DTA trajectories for PSI induced particles eroded by a Lunar lander (including terrain details)



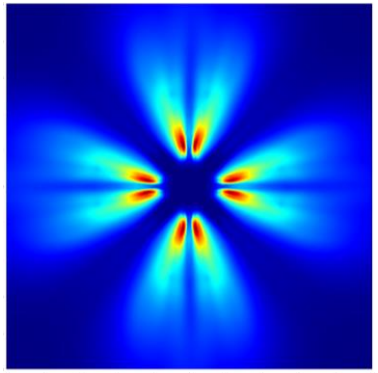
DTA predictions of PSI liberated regolith distribution around example Lunar landing site

- Primary metrics include particle trajectories, impact velocity and kinetic energy, debris fields, and keep-out zones
- Enables rapid parametric exploration of particle shapes/sizes/densities of eroded particles for dilute solid phase regions of PSI plume/regolith flows especially for dilute regions such as occurring in VSE or far field
- Assumes 1-way coupling from fluid to particle without particle/particle interactions

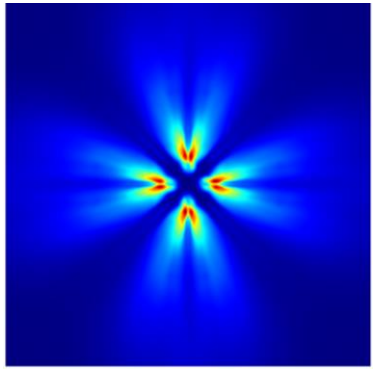
Descent Interpolated Gas Granular Erosion Model (DIGGEM)

- The DIGGEM tool predicts PSI cratering through a descent (or ascent) trajectory using inputs of erosion rate at a few fixed altitudes. Fixed altitude erosion rates could come from either CFD or experimental results.
- The tool interpolates erosion rates at intermediate altitudes and integrates these in time/altitude to get the time evolving crater shape throughout the trajectory.

Eroded mass flux at one altitude



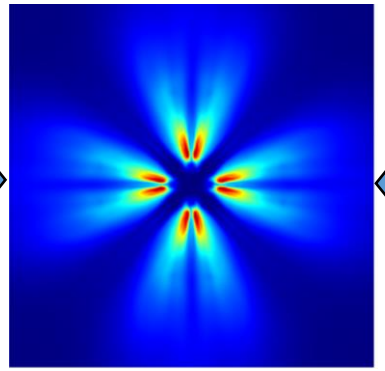
Eroded mass flux at 2nd altitude



Map mass flux to common reference mesh



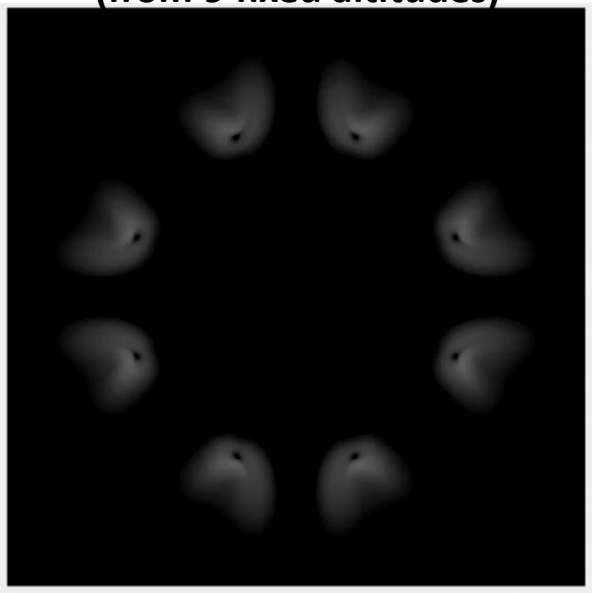
Interpolate mass flux at intermediate altitudes between CFD solutions



Map mass flux to common reference mesh



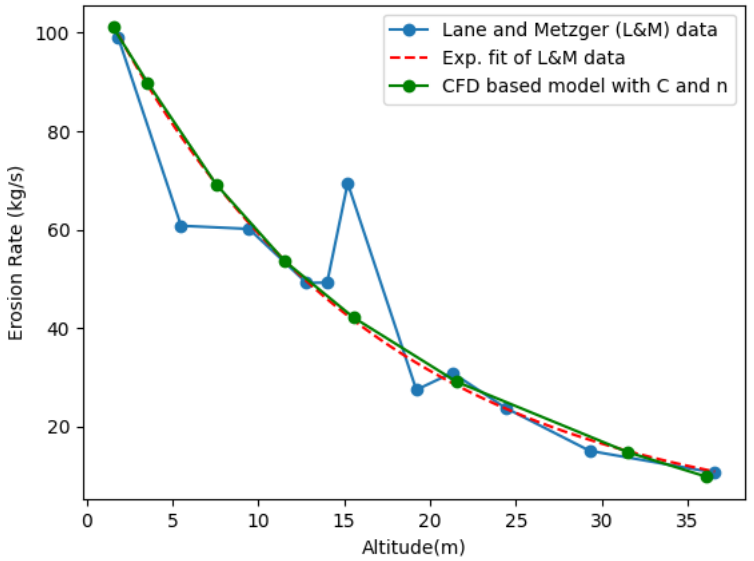
Animation of DIGGEM erosion flux during descent of vehicle with 8 engines (from 9 fixed altitudes)



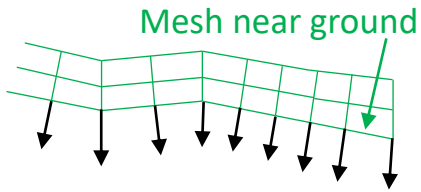
Loci/CHEM-DIGGEM

- An engineering erosion model has been implemented in Loci/CHEM-DIGGEM using 3 modules to allow fully coupled dynamic descent calculation of VSE regime cratering
- Engineering Model of viscous shear erosion has been calibrated using data derived from Apollo flight

Comparison of calibrated model to Apollo data

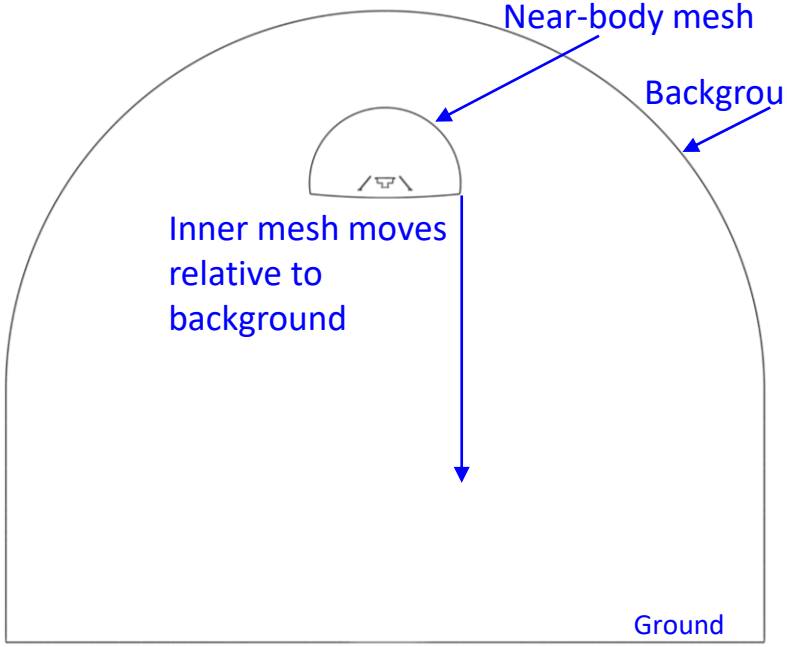


2) gridMotion module



Deformation of mesh nodes in direction normal to surface

3) componentMotion module



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

1) sufaceErosionFlux module

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

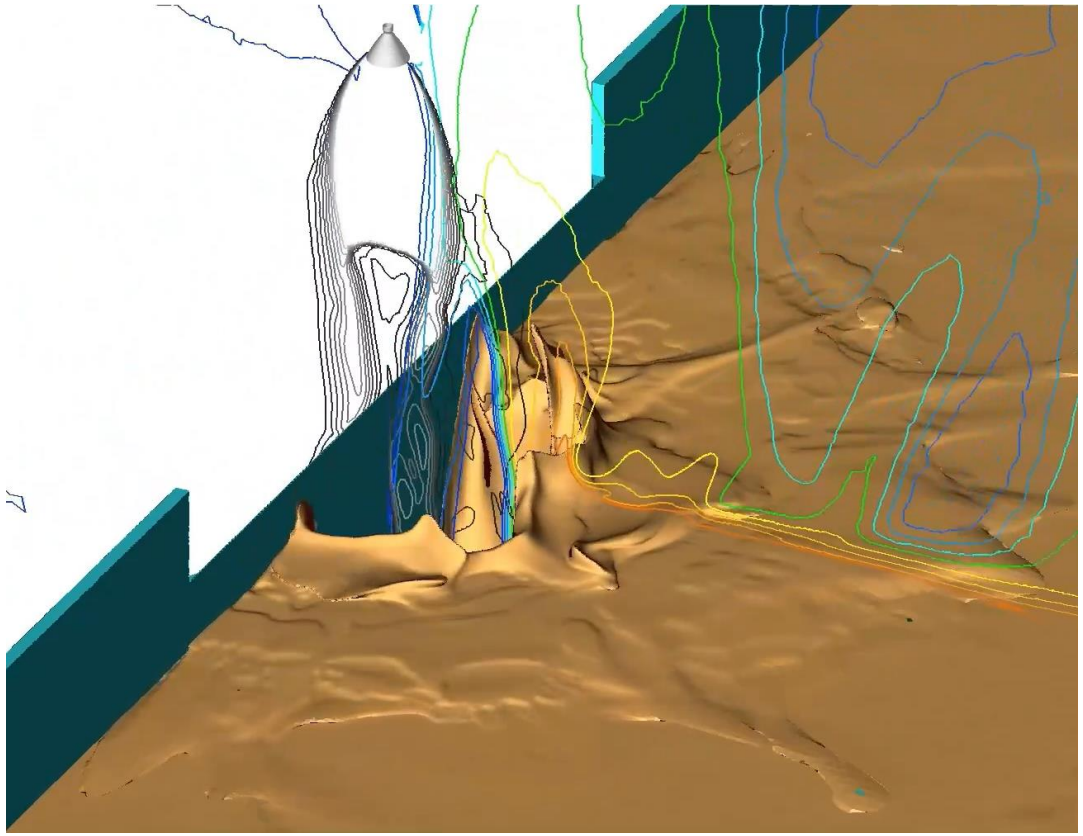
Engineering model of VSE erosion rate used in Loci/CHEM-DIGGEM

$$\Delta d(x,y,t) = -[mass_flux\ (x,y,t)/\rho]\Delta t$$

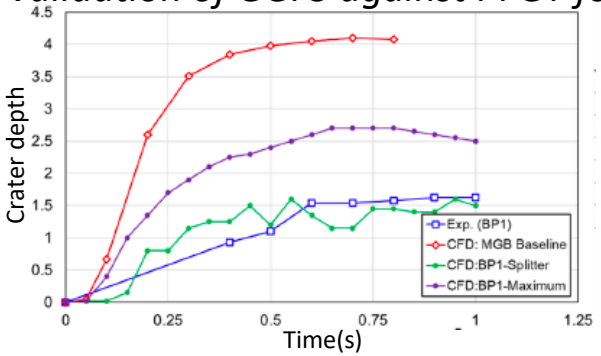
Specifies deflection used in the gridMotion module at each timestep to be a function of the mass flux (from engineering model) and regolith/soil density

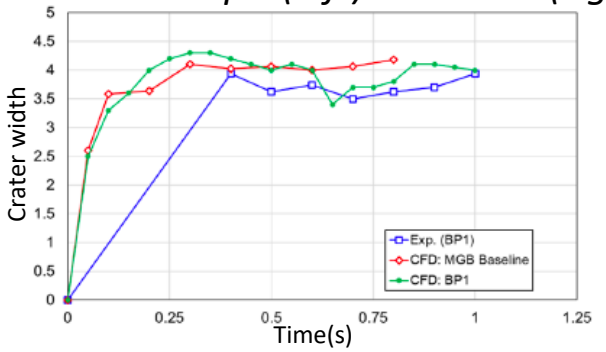
Gas Granular Flow Solver (GGFS)

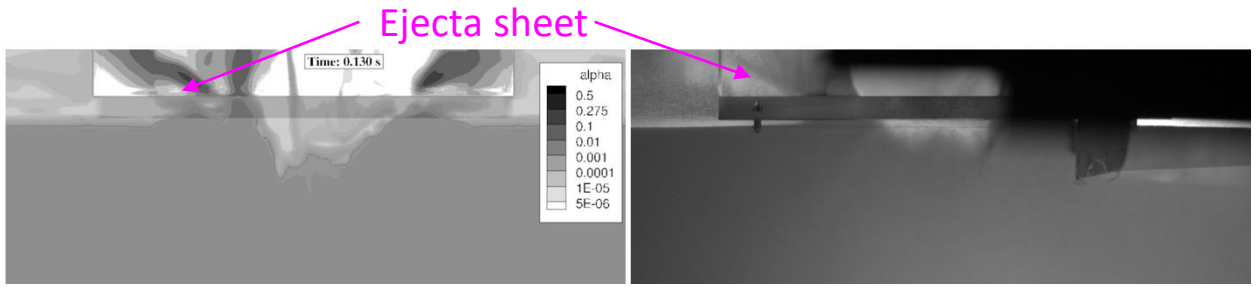
- GGFS is an Eulerian/Eulerian CFD tool that simultaneously solves the multiphase gas/regolith flow field
- In addition to VSE, GGFS enables simulation of highly complex physics including regolith bed fluidization, diffusion driven flow (DDF) erosion regime, diffuse gas erosion (DGE), ejecta sheets and filaments, and redeposition of eroded material (See figure/video at lower left)
- Can be used to obtain fixed altitude erosion rates to allow DIGGEM to predict crater formation over entire descent trajectory for DDF regime
- Initial validation for both ejecta and cratering using Physics Focused Ground Test (PFGT) data



Validation of GGFS against PFGT for DDF crater depth(left) and width(right)







Validation of GGFS(left) against PFGT(right) for DDF ejecta

Summary

- MSFC Fluid Dynamics Branch is currently using this suite of tools for predictive modeling of PSI, enabling assessment of risk and design decisions for
  - Human Lander System (HLS)
  - Commercial Payload Services (CLPS)
  - Stereo Cameras for Lunar Plume Surface Studies (SCALPSS)
  - HLS providers
  - Lunar site planning
  - Moon2Mars Mars Lander Architecture

- This suite of tools is being continuously improved
  - Additional and more rigorous validation against additional existing and emerging datasets
  - Cross integration – allowing multiple tools to be used in the same ecosystem for improved coupling
  - Capability expansion – additional soil models, multi-dispersity of particulate
  - Improved efficiency – optimization of computational methods and algorithms, extension to allow GPGPU implementation

- Significant interest/pull from customers regarding PSI induced dust environment metrics, including volumetric loading, visibility obscuration, and surface accumulation has driven current efforts to expand this tool suite to include these capabilities in the near future


Questions?